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3 **Impact of natural (waves and currents) and anthropogenic (trawl) resuspension on the export**  
4 **of particulate matter to the open ocean. Application to the Gulf of Lion (NW Mediterranean)**

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9 **ABSTRACT**

10

11 Modern sediment deposits on continental margins form a vast reservoir of particulate matter that is  
12 regularly affected by resuspension processes. Resuspension by bottom trawling on shelves with  
13 strong fishing activity can modify the scale of natural disturbance by waves and currents. Recent field  
14 data show that the impact of bottom trawls on fine sediments resuspension per unit surface is  
15 comparable with that of the largest storms.

16 We assessed the impact of both natural and anthropogenic processes on the dispersal of river-borne  
17 particles and shelf sediments on the Gulf of Lion shelf. We performed realistic numerical simulations of  
18 resuspension and transport forced by currents and waves or by a fleet of bottom trawlers. Simulations  
19 were conducted for a 16-month period (January 1998 - April 1999) to characterise the seasonal  
20 variability. The sediment dynamics takes into account bed armoring, ripple geometry and the cohesive  
21 and non-cohesive characteristics of the sediments. Essential but uncertain parameters (clay content,  
22 erosion fluxes and critical shear stress for cohesive sediment) were set with existing data.  
23 Resuspension by waves and currents was controlled by shear stress, whereas resuspension by trawls  
24 was controlled by density and distribution of the bottom trawler fleet.

25 Natural resuspension by waves and currents mostly occurred during short seasonal episodes, and  
26 was concentrated on the inner-shelf. Trawling-induced resuspension, in contrast, occurred regularly  
27 throughout the year and was concentrated on the outer shelf. The total annual erosion by trawls  
28 ( $5.6 \times 10^6 \text{ t y}^{-1}$ , t for metric tonnes) was four orders of magnitude lower than the erosion induced by  
29 waves and currents ( $35.3 \times 10^9 \text{ t y}^{-1}$ ). However the net resuspension (erosion/deposition budget) for  
30 trawling ( $0.4 \times 10^6 \text{ t y}^{-1}$ ) was only one order of magnitude lower than that for waves and currents  
31 ( $9.2 \times 10^6 \text{ t y}^{-1}$ ).

32 Off-shelf export concerned the finest fraction of the sediment (clays and fine silts) and took place  
33 primarily at the southwestern end of the Gulf. Off-shelf transport was favoured during the winter 1999  
34 by a very intense episode of dense shelf water cascading. Export of sediment resuspended by trawls  
35 ( $0.4 \times 10^6 \text{ t y}^{-1}$ ) was one order of magnitude lower than export associated with natural resuspension  
36 ( $8.5 \times 10^6 \text{ t y}^{-1}$ ). Trawling-induced resuspension is thought to represent one third of the total export of  
37 suspended sediment from the shelf.

38 A simulation combining both resuspension processes reveals no significant changes in resuspension  
39 and export rates compared with the sum of each individual process, suggesting the absence of  
40 interference between both processes.

41 Keywords: Sediment dynamics; Sediment transport; Shelf–slope exchanges; Fisheries; Trawling;  
42 Mediterranean

43 **1. INTRODUCTION**

44 Continental margins are located at the edges of continents and form a buffer zone where the oceans,  
45 continents and atmosphere interact. Significant quantities of organic and inorganic material are input  
46 to continental margins where intense hydrodynamic conditions control their dispersal on the shelf and  
47 towards the open sea. The sedimentary compartment on continental margins appears to be a vast  
48 reservoir of particulate matter, in particular river-derived material, and also of dissolved constituents.  
49 Resuspension of sediment causes a significant redistribution of sediments and has important  
50 implication for regional particulate matter budgets and export to deeper environments, i.e. the  
51 continental slope and rise.

52

53 Nowadays the physical resuspension and disturbance of sediment on continental shelves is a  
54 combination of both natural and anthropogenic mechanisms. Waves and currents are the major  
55 initiators of natural disturbance that can result in potentially massive sediment redistribution. The  
56 large-scale disturbance they induce can be periodic, when associated with tidal currents, or episodic,  
57 when associated with storms. On the other hand, commercial bottom trawling has a more reduced and  
58 patchy print. Bottom fishing gears (trawl, dredge) efficiently scrape the superficial sediment and  
59 generate suspended sediment plumes. In many shelves fishing intensity is high and most fishable  
60 grounds, which can extend to 1000 m in depth, are likely to be disturbed more or less frequently. The  
61 effect of sediment resuspension by waves and currents and bottom trawling is site-specific, as it  
62 depends on hydrodynamic conditions (storm frequency and intensity, tidal motions), sediment  
63 characteristics (grain size, cohesiveness), and fishing activity (frequency and geographical distribution  
64 of bottom hauls, gear type).

65

66 The relative contribution of each mechanism to the resuspension and export of sediment on  
67 continental shelves has seldom been addressed. To our knowledge, Churchill (1989) and DeAlteris *et*  
68 *al.* (1999) carried out the only preliminary studies on the comparison of the effect of natural and  
69 anthropogenic resuspension on different areas of the Mid-Atlantic Bight (Narraganset Bay, Nantucket  
70 Shoals, and Virginia Shelf). These studies concluded that natural physical processes are the primary  
71 suspension mechanism in shallow environments, where they disturb the bed regularly, while trawling  
72 appears to be the primary resuspension mechanism in deeper environments where natural processes  
73 are weaker and rarely capable of eroding sediment. Furthermore, Churchill (1989) estimated, using  
74 current meter data and simple analytical models, that transport of sediment resuspended by trawlers  
75 on muddy regions of the outer shelf could contribute to the off-shelf transport of particulate matter.

76

77 The present paper aims to assess the impact of sediment resuspension on particulate matter budgets  
78 on the Gulf of Lion continental shelf (NW Mediterranean). It discriminates the impact of natural  
79 physical (waves and currents) and anthropogenic (bottom trawling) processes, and thereby evaluates  
80 whether anthropogenic disturbance represents a significant or just a slight modification in the scale of

81 existing natural disturbance. This work uses three-dimensional numerical models coupling the  
82 hydrodynamics with the sediment dynamics associated with waves and currents and/or trawling. The  
83 parameterizations used in the models are based on experimental studies of the resuspension of fine  
84 sediments by intense storms (Ferré *et al.*, 2005; Ulses *et al.*, this volume) and trawls (Durrieu de  
85 Madron *et al.*, 2005). Simulations over one annual period, using realistic forcings, were carried out to  
86 characterise and quantify (i) the temporal variability and magnitude of sediment resuspension on the  
87 shelf, (ii) the dispersal of resuspended sediment, and (iii) the export towards the open sea.

88

89 The outline of this paper is as follows: the regional setting is described in section 2, the  
90 hydrodynamical and sediment transport models are briefly described in section 3, the numerical  
91 simulations of sediment resuspension and export are exposed in section 4, comparison of  
92 resuspension processes and their impact of the sediment budgets are presented in section 5, a  
93 summary is given in section 6, and the model equations are given in the appendix.

94

95

## 96 **2. REGIONAL SETTING**

### 97 **2.1. Physiography and hydrodynamics**

98 The Gulf of Lion is a non-tidal and river-dominated margin in the northwestern Mediterranean (Fig.  
99 1a). It is fed by ten rivers, one of them being the Rhône, which is the major Mediterranean river. Its  
100 crescent shape and the circulation patterns favour off-shelf export of particulate matter at the  
101 southwestern end of the Gulf (Monaco *et al.*, 1999; Heussner *et al.*, 2006, Palanques *et al.*, 2006).

102 The grain size distribution of superficial bottom sediments is shown in Fig. 1b. Sands of the inner shelf  
103 display a seaward-fining texture and merge with mid-shelf muds in water deeper than 20–30 m. The  
104 only noticeable exception is the prodeltaic accumulation zones found near river mouths, which are  
105 composed of silty muds. Muddy deposits on the outer shelf (>90 m) are mixed with relict sandy  
106 outcrops.

107 The different wind regimes determine the natural resuspension and transport of suspended sediment  
108 on the shelf. Predominant N-NW winds generally induce distinctive and opposing circulation cells on  
109 the shelf, favouring intrusion of slope waters in the eastern and central parts, and export of shelf water  
110 at the southwestern end of the Gulf (Estournel *et al.*, 2003; Petrenko *et al.*, 2004, Ulses *et al.*, in  
111 press)). Furthermore, these cold and dry continental winds are responsible for the strong cooling and  
112 homogenisation of the shelf water column during winter, and eventually generate dense water (Dufau-  
113 Julliand *et al.*, 2004; Ulses *et al.*, in press). Due to the reduced fetch, N-NW winds generate small  
114 waves (significant wave height < 2 m, peak period < 6 s) on the inner shelf. Episodic and short-lived  
115 E-SE winds induce a sea level rise at the shore and an overall intense cyclonic circulation on  
116 the shelf (Ulses *et al.*, in press). These winds are, are associated with a long fetch and large swell

117 (significant wave height up to 10 m, peak period up to 12 s). River floods often occur in conjunction  
118 with E-SE storms as the transport of humid marine air over coastal relief induces abundant  
119 precipitation. Resuspension by natural physical processes results primarily from the effect of  
120 southeasterly swells associated with E-SE winds (Ferré *et al.*, 2005, Guillén *et al.*, 2006).

121 A permanent cyclonic current (the Northern Current) flows along the slope and is part of the general  
122 circulation of the western Mediterranean basin (Millot, 1999). It forms a density front that separates the  
123 low-salinity shelf water from the more saline open sea water, limiting the off-shelf dispersal while  
124 enhancing along-slope dispersal (Durrieu de Madron *et al.*, 1990; Lapouyade and Durrieu de Madron,  
125 2001).

126 Hence, constrained by the slope current offshore and the coast inshore, most shelf water and  
127 suspended sediments are funneled towards the narrowing southwestern shelf end. They are  
128 advected out of Gulf of Lion's shelf, by flowing alongshore around the Cape Creus promontory or  
129 down the nearby canyons.

130

## 131 **2.2. Characteristics of trawling activity**

132 About 128 trawlers coming from the local fishing ports (Port-Vendres, Port-la-Nouvelle, Agde, Sète,  
133 Grau du Roi, Port de Bouc) are working in the Gulf of Lion, using either semi-pelagic or bottom trawls  
134 to catch demersal fish species. Bottom trawlers use single trawl nets tightened between doors (otter)  
135 with a tickler chain as a groundrope. Pelagic trawls are sometimes also used very near the seabed,  
136 but Durrieu de Madron *et al.* (2005) showed that they had no impact on the sediment resuspension.  
137 The daily number of trawlers using bottom trawls ranges approximately between 40 and 90 boats,  
138 each trawler performing 4 to 5 tows of about 2 hours daily. They work throughout the year except  
139 weekends and public holidays.

140 Fishing grounds cover the whole continental shelf except for a 3-mile coastal band, where all trawling  
141 activity is banned. A survey conducted with fishermen revealed that the wind is the principal criterion  
142 for the choice of the fishing grounds. Trawlers remain basically close to the coast during strong winds  
143 ( $> 10 \text{ m s}^{-1}$  or 20 knots) and rough seas state periods, and move to the outer shelf for weaker winds  
144 and calmer sea state..

145

## 146 **3. MATERIAL AND METHODS**

### 147 **3.1. Hydrodynamical model**

148 *The SYMPHONIE Model* - The three-dimensional primitive equation coastal ocean model  
149 SYMPHONIE, used in this study, has been extensively validated in the Gulf of Lion. It was previously  
150 used to study the Rhône river plume (Estournel *et al.*, 1997; Marsaleix *et al.*, 1998; Estournel *et al.*,  
151 2001), the intrusion of the Northern Current into the shelf (Petrenko *et al.*, 2004), the wind-induced  
152 circulation (Estournel *et al.*, 2003) and the formation of dense water on the shelf and its cascading  
153 over the slope (Dufau-Julliand *et al.*, 2004; *Ulses et al.*, accepted).

154  
155 The horizontal and vertical components of the current, free surface elevation, temperature and salinity  
156 are computed on a C staggered-grid (Arakawa and Suarez, 1983). A generalized topography following  
157 co-ordinate system is used. Compared to simple sigma coordinate, the generalized sigma coordinate  
158 allows the slope of the iso-level surface to be limited over steep topography in order to avoid large  
159 truncation errors on the pressure gradient computation (Auclair *et al.*, 2000). The turbulence closure  
160 scheme is based on a prognostic equation for the turbulent kinetic energy and on a diagnostic  
161 equation for the mixing and dissipation length scales (Bougeault and Lacarrère, 1989). A leap frog  
162 scheme is used for the time-stepping. A time-splitting technique (Blumberg and Mellor, 1987) allows  
163 the vertical shear of the current and the depth-averaged horizontal components to be computed  
164 separately with appropriate time steps. The time step of the model is set to 180 s.

165  
166 *Initialisation and boundary conditions* - The domain of the Gulf of Lion model (25 vertical levels and 3  
167 km horizontal resolution grid) is presented in Figure 1a. The main boundary of the modelling domain  
168 has been chosen to be parallel to the continental slope.

169  
170 At the surface, the momentum flux is equal to the wind stress. The heat flux results from the  
171 atmospheric fluxes (sensible and latent heat fluxes) and from the radiative fluxes (both short and long  
172 wavelengths), the salinity flux is calculated from evaporation. Concerning the flux of turbulent kinetic  
173 energy, the usual boundary-layer balance between production and dissipation is applied. The wind  
174 stress and the heat fluxes are computed with the bulk formulae (Geernaert, 1990) using 6-hours  
175 outputs of the high resolution meteorological models ARPEGE and ALADIN from Météo-France  
176 (surface pressure, air temperature, relative humidity and wind velocity) and the sea surface  
177 temperature is computed by the ocean model.

178  
179 At the sea floor, the near-bottom stress is related to the horizontal bottom velocity and waves, as well  
180 as the seabed roughness. A detailed description of this term is given in appendix 2. Heat and salinity  
181 fluxes are considered to be zero at this boundary. The flux of turbulent kinetic energy is parameterised  
182 similarly as the one at the surface boundary.

183  
184 At open lateral boundaries, the free-surface elevation ( $\eta$ ) and the component of transport orthogonal to  
185 the boundary ( $U$ ) are given by the radiation condition of Oey and Chen (1992):  $U=U_0 \pm (gH)^{1/2} (\eta-\eta_0)$ .  
186 Others variables are given by  $\nabla_H \phi = \nabla_H \phi_0$ , where  $\phi$  stands for the tangential component of the depth

187 averaged current and baroclinic velocities.  $U_0$ ,  $\varphi_0$  and  $\eta_0$  refer to the large scale field forcing.  
188 Concerning temperature and salinity, an upstream condition implies that large-scale fields,  $T_0(t)$  and  
189  $S_0(t)$ , are advected into the simulated domain under inflow conditions. The large-scale fields are also  
190 applied over the whole grid at  $t=t_0$  (initialisation). This initial state aims to start the simulation with the  
191 large-scale geostrophic circulation of the Gulf of Lion, generally identified as the Northern Current. The  
192 model is initialised with a fully established along slope circulation adjusted to bathymetry constraints,  
193 based on a linearised derivation of the external mode equations of the model (Estournel *et al.*, 2003).  
194 The regional model was initialized and forced every day by the large scale Ocean General Circulation  
195 Model (OGCM) MOM outputs. Wave characteristics over the domain were described by the 6-hour  
196 outputs of the Vagmed waves-forecast model of Météo-France.

197  
198 Concerning the buoyancy inputs, the freshwater inputs for the main rivers of the Gulf of Lion (Grand-  
199 Rhone, Petit-Rhone, Vidourle, Lez, Hérault, Orb, Aude, Agly, Têt, Tech) (see Fig. 1a), are taken into  
200 account. Daily discharges provided by the 'Compagnie Nationale du Rhône' and by the 'Banque  
201 Hydro-MEDD/DE' were specified at the ten river mouths. The temperature in all rivers is set following  
202 measurements in Rhone river (Poirel *et al.*, 2001), with a maximum value of 22 °C in October and a  
203 minimum value of 7 °C in January and February.

204

### 205 **3.2. Sediment transport model**

206 The suspended sediment transport model aims at simulating the dispersal of the sedimentary particles  
207 resuspended by waves and currents, as well as bottom trawls. This model is governed by an  
208 advection-diffusion dispersion equation, and considers different particle grain sizes (see appendix 1).  
209 Deposition and erosion terms are incorporated into the seabed boundary condition. The erosion term  
210 was estimated with sediment dynamic models specific to each resuspension mechanisms (waves and  
211 current, trawl); they are described in the following chapters and in appendix 2.

212 Given that the Gulf of Lion sediments cover a wide range of size (Fig. 1b), primary (individual) particles  
213 in the sediment were clustered in 7 size classes ranging from clay to coarse sand, according to the  
214 Wentworth classification (1922). Two additional classes were considered for suspended particles to  
215 take into account aggregated particles. The aggregates characteristics were inferred from  
216 comparisons between *in situ* and laboratory particle size distribution of resuspended sediment (Durrieu  
217 de Madron *et al.*, 2005). These measurements suggested that about  $\frac{3}{4}$  of the clays and  $\frac{1}{4}$  of the fine  
218 silts are incorporated into aggregates whereas the rest remains as primary particles. We considered  
219 that clays and fine silts contributed equally to the formation of both classes of aggregates. The  
220 characteristics of each class (median grain size, settling velocity and density) are indicated in the  
221 Table 1.

222 River sediment inputs were computed using water discharge ( $Q$ ) and suspended sediment  
223 concentration estimates ( $SSC=f(Q)$ ) established by different authors: Sempéré *et al.* (2000) for the  
224 Rhône River, Petelet-Giraud *et al.* (2003) for the Hérault River, Serrat (1999) for the Agly River, and

225 Serrat *et al.* (2001) for the Têt River. In absence of information for Orb and Aude Rivers, we used the  
226 relationship of the nearby Herault River. Finally, solid discharge of the Rhône River was divided into  
227 two parts: 90% for the Grand-Rhône branch and 10% for the Petit-Rhône branch. Grain size  
228 distribution of river inputs was defined according to recent data collected in the Rhône River  
229 (Radakovitch, personal communication) and Têt River (Garcia-Esteves, 2005). All “small” rivers  
230 (Hérault, Agly, Orb, Aude, Vidourle and Tech) are considered to have the same grain distribution as  
231 the Têt River. Most of the suspended particles are silts (ca 80% for the Rhône River and 69% for the  
232 Têt River) and clays (~ 18% for the Rhône River and 24% for the Têt River). The sediment provided  
233 by the rivers is homogeneously input in one mesh, and settles and/or is transported as it enters the  
234 domain.

235 The grain size distribution of the shelf surface sediments was determined from the compilation of  
236 several sedimentological surveys that provided about 160 cores over the whole shelf. Figure 1b shows  
237 the median grain size of the first centimetres of the sediment. Maps of the fraction of the different size  
238 classes were used at the initial time. Their characteristics slightly changed throughout the simulation  
239 according to the dispersal of river inputs, and the erosion and deposition of the different classes of  
240 sediment.

### 241 **3.3. Sediment dynamics for waves and currents**

242 The sediment erodability is controlled by the shear stress intensity and the bottom sediment properties  
243 (coarse non-cohesive vs. fine cohesive sediments). The limit between cohesive and non-cohesive  
244 sediment was fixed at 10 % of clay (<2  $\mu\text{m}$ ), which is in the range (3-14%) defined in various studies  
245 (Dyer, 1986; Torfs, 1995; Panagiotopoulos *et al.*, 1997; Houwing, 2000). The Partheniades' law (1962)  
246 was used to compute the erosion flux of cohesive sediments, whereas the reference concentration  
247 based on the method of Zyserman and Fredsøe (1994) was used for the erosion flux of the non-  
248 cohesive sediments (see appendix 2).

249 The stress values were computed using combined wave and currents conditions, and discriminated  
250 flat-bed and rippled bed conditions (see appendix 2). The bottom roughness calculation and ripple  
251 geometry for the non-cohesive sediments were based on the SEDTRANS96 model (Li and Amos,  
252 1998; Li and Amos, 2001), which predicts the roughness and bedforms generated by a combined  
253 wave/current model. For cohesive and mixed sediments, the roughness scale model of Harris and  
254 Wiberg (2001) was used. Besides, bed armoring was implemented in the model to take into account  
255 the reduction of erosion flux of fine particles in mixed sediments, due to the protective effect of larger  
256 sand grains (Harris and Wiberg, 2001).

257 The critical shear stress (stress above which the sediment is likely to be removed) depends on grain  
258 size and sediment characteristics. For non-cohesive sediments, the critical shear stress is given in the  
259 form of a critical Shields parameter value, which depends on the grain size of each class (see  
260 appendix 2). For cohesive sediments, the threshold value is difficult to establish because it depends  
261 on the compaction and history of the sediment. Indeed, an unconsolidated surface layer (fluff) is



262 eroded for very weak shear stresses, ranging between 0.02 and 0.08 N m<sup>2</sup> (El Ganaoui *et al.*, 2004;  
263 Gust and Morris, 1989; Maa *et al.*, 1998; Schaaff *et al.*, 2002). The underlying, more consolidated  
264 layers, need larger critical shear stresses, between 0.1 and 0.61 N m<sup>2</sup> (Maa *et al.*, 1998; Houwing,  
265 1999; Krishnappan and Marsalek, 2002, Palanques *et al.*, 2002). In this study the model does not  
266 include a fluff layer, and all of the cohesive sediment is given an average critical shear stress of 0.2  
267 N m<sup>-2</sup>.

268

### 269 **3.4. Resuspension by bottom trawls**

270 In absence of direct information of distribution and movement of trawlers on the shelf (such as those  
271 provided by Vessel Monitoring System), we used a probabilistic approach and the fishing rules in force  
272 in the area to simulate their daily position and trajectory. Based on sample surveys of the fishermen  
273 population of the different ports about their preferential fishing grounds and depths, we derived an  
274 average trawling activity within a daily operating range from each port. These fishing patterns were  
275 generalized to the trawling fleet of each port, and the total fishing intensity in every locations of the  
276 shelf was derived by summing the effect of all fleets. The scores assigned to each location of the shelf  
277 area were finally used to weight partition the total fishing effort (Fig. 2). A distribution of fishing effort  
278 was simulated for wind speeds lower and larger than 10 m s<sup>-1</sup>; the sea state being determinant for the  
279 choice of fishing grounds. The daily working time and number of active bottom trawlers was estimated  
280 from records of trawler fleet coming from the different fishing ports (Fig. 3d). During working days (i.e.,  
281 apart from weekends and public holidays), each trawler was assumed to perform 4 tows of 2 hours  
282 from 4 a.m. to 12 a.m.

283 The distribution map for each working day was selected according to the wind intensity next to the  
284 Sète port (major fishing port of the area) at 4 a.m. After being positioned randomly, each trawl was  
285 displaced using a random walk approach. Given the mesh size of the model (3 km) and the trawling  
286 speed (1.5 m s<sup>-1</sup>), a crossing time of 33 min was considered before moving each trawler to one of the  
287 surrounding mesh. After this time, the 8 surrounding cells have the same probability to be trawled. A  
288 maximum number of 3 trawlers per mesh was imposed, to take into account interaction among fishing  
289 vessels. Albeit schematic, the simulated spatial allocations is believed to correctly reproduced the  
290 distribution of bottom trawling effort and displacement of vessels, but probably under estimate trawling  
291 activity in banned areas (e.g., within the 3-miles coastal band).

292 The fluxes of sediment resuspended by otter bottom trawls and the characteristics of the sediment  
293 plumes were estimated experimentally and described by Durrieu de Madron *et al.* (2005). They  
294 showed that resuspension fluxes depend on the trawls groundrope gears, but above all, on sediment  
295 texture, i.e., fluxes increase with increasing clay content. Based on the measurements performed by  
296 Durrieu de Madron *et al.* (2005), a linear relationship was derived between the resuspension flux and  
297 the clay fraction (see appendix 2). According to observations, resuspended sediment was distributed  
298 over the last 5 m above the seabed with a concentration inversely proportional to the seabed distance.

299 For each time step (180 s), the resuspended mass of sediment in the model is calculated according to  
300 the clay fraction and is proportional to the trawled area: 4320 m<sup>2</sup> considering a trawler speed of 1.5 m  
301 s<sup>-1</sup>, and a combined net and door width of 16 m. Because this area is much smaller than that of the  
302 model's mesh (9 km<sup>2</sup>), the resuspended mass was spread over the entire mesh and within layers  
303 including the last 5 m above bottom. The bias introduced by the forced diffusion is likely to be small,  
304 since most of the resuspended sediment is rapidly deposited (within 1-2 hours according to Durrieu de  
305 Madron *et al.*, 2005), and remains confined to the adjacent meshes.

### 306 **3.5. Scenarios and numerical solutions**

307 Four scenarios were carried out in order to answer the question about the role of resuspension in the  
308 shelf-slope exchanges of particulate matter. They considered the same hydrodynamic forcings  
309 described in chapter 3.1.

- 310 - The first simulation, which only takes into account the river particulate inputs, (i.e. resuspension is  
311 absent), was used as reference for the shelf deposit and the export of riverine particulate matter  
312 for the study period;
- 313 - The second scenario considered, in addition to the preceding simulation, resuspension of  
314 sediment by currents and waves only;
- 315 - The third scenario considered the sediment resuspension by trawls only;
- 316 - A fourth scenario combining resuspension by waves and currents, as well as trawls, checked if  
317 there is any significant non linear effect.

318 Simulations lasted 16 months from January 1, 1998 to April 1, 1999. The water column was clear of  
319 suspended particles at the initial time, and the system was gradually loaded in suspended particles,  
320 coming from rivers and/or sediment resuspension during the first months of simulations. As the  
321 residence time of shelf waters is about 2 months (Durrieu de Madron *et al.*, 2003), we checked that the  
322 suspended sediment concentration (SSC) of the shelf water was stabilized on the third month (March  
323 1998). For each scenario, annual budgets of resuspended sediment, deposited particles on the shelf,  
324 and exported particles to the slope, were calculated between April 1998 and April 1999. The shelf-  
325 edge for these calculations is defined as the 200-m isobaths, and confined between Cape Creus and  
326 Cape Couronne (cf. Fig. 1a for the boundary). Sediment export from the Gulf of Lion's shelf is  
327 calculated by the difference between the resuspension and the deposition on the shelf and at each  
328 time step, and then by subtracting the sediment present in the water column.

329 Hydrology and circulation on the shelf and upper slope were measured for two surveys conducted in  
330 March/April 1998 and January 1999. Previous studies tested the ability of the hydrodynamical model  
331 to correctly reproduce the hydrology and the wind-induced circulation patterns observed in March/April  
332 1998 (Estournel *et al.*, 2003), and the formation of dense water on the shelf and its cascading over the

333 slope in January/February 1999 (Dufau-Julliand *et al.*, 2004). Critical but indefinite parameters of the  
334 sediment dynamics model (i.e., clay content threshold for cohesive/non-cohesive behaviour, erosion  
335 flux and critical shear stress for cohesive sediments) were adjusted to fit the *in situ* observations  
336 collected all over the shelf during these surveys. Parameters were chosen in order to have the  
337 smallest relative error ( $|SSC_{in\ situ} - SSC_{model}| / SSC_{in\ situ}$ ), keeping in mind that measured  
338 concentrations include other sources of particulate matter (atmosphere, rivers, biology or advection  
339 onto the domain) which are not taken into account in the model. For these reasons, stations nearby  
340 the Rhône river mouth, nearby the slope or outside of the shelf are not used because they are likely to  
341 contain a majority of particles which are not from resuspension. The location of the casts used for  
342 comparison is shown in Fig. 1a. The agreement was quantified by computing the relative error  
343 between simulated SSC values (combining both resuspension by waves and current conditions and  
344 trawling activity) within the last three levels above the bottom with observed near-bottom SSC,  
345 estimated from optical (light transmission) measurements. This comparison is possible because of a  
346 weak fluorescence during the surveys ( $< 0.2$  on the Gulf of Lion), indicating a negligible biological  
347 fraction. Extreme parameters from the literature were first tested and the adjusted parameters yielded  
348 a relative error in SSC less than 35% for more than half of the stations and maximum differences of  
349 80%.

## 350 4. RESULTS

### 351 4.1. Hydrodynamical conditions.

352 During the simulation period (April 1998 – April 1999) the Rhône River supplied respectively 80% of  
353 the freshwater and 90% of the suspended sediment inputs to the Gulf (Fig. 3a). The annual total solid  
354 discharges amounted to  $3.6 \times 10^6$  t (metric tonnes), that were supplied during medium floods occurring  
355 mostly during the spring 1998 and late autumn 1998-winter 1999 (Fig. 3b). Given that the average  
356 sediment discharge from the Rhône over the 1977-2004 period is about  $10.1 \times 10^6$  t  $y^{-1}$  and peaks at  
357 more than  $33 \times 10^6$  t  $y^{-1}$  (Bourrin *et al.*, 2007), the 1998-1999 period appears as a low discharge year.

358 E-SE gales were rare and brief but caused locally strong precipitations and sudden floods. N-NE  
359 continental winds were predominant throughout the year (Fig. 3c). These cold and dry winds affected  
360 the annual cycle of the shelf water thermal characteristics, by inducing strong mixing and cooling  
361 during fall and winter. As the average salinity of the shelf water was rather constant all over the year,  
362 decreasing temperature induced a progressive increase of density that culminated in late winter (Fig.  
363 3f). During winter 1999, dense shelf water overflowed the shelf break and cascaded down the slope .  
364 Export of water mainly occurred in the western part of the shelf, and was compensated by an inflow in  
365 the eastern part of the Gulf (Fig. 3g). Béthoux *et al.* (2002) showed that an event of such intensity had  
366 not occurred since 1993, and that the last event probably went back to the winters 1987-1988. An  
367 event of similar intensity was observed in winter 2005 (Canals *et al.*, 2006).

368 Bottom stress presents a seasonal cycle with larger values between the end of autumn and the  
369 beginning of spring (Fig. 3e), due to the increase of the current intensity and wave conditions, and also  
370 to the weak stratification or even vertical homogeneity of the shelf water. Wind intensity and direction  
371 variability induced many bursts in the bottom stress, which was generally more intense on the western  
372 part of the shelf.

373 In summary, the study period was characterized by low river discharges and moderate wave  
374 conditions (with few E-SE storms), but by intense winter shelf water export through dense water  
375 cascading caused by sustained N-NW winds.

376

#### 377 **4.2. Fate of river inputs without resuspension.**

378 A first simulation was carried out by taking into account the sediment supplied by rivers only, in order  
379 to estimate the direct contribution of rivers to the sediment export (Fig. 4). During the April 1998 - April  
380 1999 period  $3.6 \times 10^6$  t of sediment were discharge by rivers (Table 2). As previously mentioned, most  
381 input derived from the Rhône River. Deposits of river sediment on the shelf, which amount to  
382  $3.1 \times 10^6$  t, clearly reflect the difference in river discharges (Fig. 3a). Sediments supplied by the Hérault,  
383 Orb, and Aude Rivers in the northwestern part of the Gulf remained primarily confined to the inner  
384 shelf. Deposit of the Rhône River inputs formed a wedge extending over the eastern part of the shelf  
385 and the outer shelf as far as the southwestern end of the Gulf. The net deposit thickness was largest  
386 near the major river mouth, and was about 0.1 mm on most of the shelf. The grain size distribution  
387 reflected the accumulation gradient, with an early settling of the coarser particles on the prodeltas, and  
388 a fining texture along the transport pathways. Sediments in suspension exported from the shelf were  
389 mainly composed of fine particles. The exported quantity was  $0.4 \times 10^6$  t (only 11% of river inputs  
390 (Table 2 and Fig. 5) and two thirds of the export occurred during the wintertime (Dec. 1998 – Apr.  
391 1999).

392

#### 393 **4.3. Dynamics of resuspended sediments**

394 *Resuspension and off-shelf sediment export induced by waves and currents* – Time series of the daily  
395 mass of sediment resuspended on the shelf (Fig. 6a) showed that resuspension by waves and  
396 currents appeared as short events, with a maximum duration of a few days, throughout the year.  
397 Some larger and longer resuspension events were noted in spring and fall 1998, and also during  
398 December 1998 and February 1999, due to the action of stronger coastal currents or swells. During  
399 the April 1998 - April 1999 period about  $35.3 \times 10^9$  t of sediment were resuspended (Table 2),  
400 preferentially on the inner shelf (water depth < 50 m (Fig. 7), and the largest part was composed of

401 coarse sediments that quickly settled. The annual net erosion/deposition budget amounted to  
402  $9.2 \times 10^6$  t (Table 2), which was more than twice the annual river inputs.

403 Off-shelf export occurred as bursts, which immediately followed the resuspension events. They were  
404 generally of short duration except for a sustained period in February and March 1999 due to dense  
405 shelf water cascading (Fig. 6b). Water flux at the shelf break (Fig. 3g) indicated that the two summer  
406 pulses on mid-June and mid-September 1998 occurred on the eastern part of the Gulf, while all the  
407 other episodes occurred in its western part. The annual export of sediment solely resuspended by  
408 waves and currents amounted to  $8.5 \times 10^6$  t (Fig. 5), which represented about 0.02% of the  
409 resuspended quantity (Table 2). The exported sediment was mostly composed of clays and fine silts,  
410 but the strong cascading-driven currents induced an export of larger particles (including sands) during  
411 the winter 1999.

412 The map of erosion and deposition regions at the end of the annual cycle (Fig. 7) indicated a net  
413 deposit over most of the shelf, except within the coastal band shallower than 30 m, and also on the  
414 southwestern outer shelf. Resuspension by waves and currents induced a total redistribution of the  
415 riverine sediments, but did not significantly change the initial grain size distribution of the shelf  
416 sediments (i.e., cross-shelf gradient with coarser sediment near the coast and finer sediment  
417 seaward). Regions of stronger deposit were localised along a band between 30 and 70 m deep,  
418 extending from the Rhône River as far as Cape Creus, which constitutes a natural outlet at the  
419 southwestern end of the Gulf. This band, which mimics the mid-shelf mud belt, was primarily  
420 composed of fine particles. Distinct patches of deep erosion of sediment by waves and currents were  
421 confined to the western gulf and extended to the 500 m isobath. This erosion occurred mainly during  
422 the winter cascading period and are related to the convergence and acceleration of dense bottom flow  
423 toward the southern end of the shelf and down the head of the canyons.

424  
425 The dispersal of suspended sediment on the slope was variable according to the period of the year.  
426 From May to November, while the water column was stratified, the export of shelf suspended sediment  
427 was primarily restricted to the surface slope waters (Fig. 8a). The seaward dispersal in the upper layer  
428 (0-500m) was limited by the core of the permanent cyclonic Northern Current that swept the material  
429 escaping from the shelf along the slope. From December to April, whilst the water column was weakly  
430 stratified or even unstable during the dense water cascading period, shelf suspended sediment rapidly  
431 spread into intermediate (500-1000 m) or deep (> 1000 m) slope waters (Fig. 8b).

432

433 *Resuspension and off-shelf sediment export induced by trawls* - In contrast to the natural  
434 resuspension which occurs as irregular and short episodes, bottom trawling activity is periodic and  
435 rather constant over the whole year (Fig. 3d). Resuspension by trawls is dependant on the trawl  
436 number and positions. During the April 1998 - April 1999 period, bottom trawlers worked 250 days and  
437 the fishing fleet had a daily mean strength of 63 boats. The total surface scraped by trawlers during  
438 this annual period amounted to 11,000 km<sup>2</sup>, which is comparable to the surface of the Gulf of Lion  
439 shelf (ca 12,000 km<sup>2</sup>). Some regions were trawled several times a year, whereas others were

440 untouched. For strong winds ( $> 10 \text{ m s}^{-1}$ ), trawlers were mostly confined to the coastal area, where  
441 coarse sediment is more abundant (Fig. 2a). Days of strong winds were present 13% of the year, most  
442 of the time in autumn and winter. During low wind periods ( $\leq 10 \text{ m s}^{-1}$ ), trawlers preferentially worked  
443 on the outer shelf and eroded finer sediment (Fig. 2b). About  $2.2 \times 10^4 \text{ t}$  of sediment was resuspended  
444 daily by bottom trawls (Fig. 9a), with a maximum between September and December 1998 when  
445 trawlers were more numerous ( $> 80$ , Fig. 3d). The sawtooth pattern is related to the trawling activity  
446 that stops weekends and holidays. The annual mass of sediment resuspended by trawling amounted  
447 to  $5.6 \times 10^6 \text{ t}$  (Table 2), most of it originating from depths between 80 and 130 m (Fig. 10). Considering  
448 the fraction that settled shortly after resuspension, the annual net erosion/deposition budget on the  
449 shelf amounted to  $0.4 \times 10^6 \text{ t}$  (Table 2), which was one order of magnitude less than that induced by  
450 waves- and current-induced resuspension.

451  
452 The export of resuspended sediment from the shelf showed a seasonal variability, with minimum  
453 fluxes during summertime (while the trawling-induced resuspension on shelf was maximum), and a  
454 significant increase arising from transport pulses during the winter and spring periods (Fig. 9b). The  
455 fine-grained sediment resuspended by trawlers on the outer shelf was exported primarily in the  
456 western half of the Gulf (Fig. 10). The off-shelf export added up to  $0.4 \times 10^6 \text{ t}$  annually, which accounted  
457 for ~7% of the quantity of sediment resuspended by trawling on the shelf (Table 2 and Fig. 5).

458 Transects showed that the cross-slope dispersal of the fine-grained sediment resuspended by trawlers  
459 went deeper than for the sediment resuspended by waves and currents, due probably to the proximity  
460 of regions of intense trawling activity with the shelf edge. Some sediment settles to depths of 1500-  
461 2000 m during summer stratified condition (Fig. 11a). Cascading of dense water during winter caused  
462 a rapid advection of turbid shelf water down to 1000 m deep, and settling favoured the spreading of  
463 suspended sediment as far as 2000 m deep (Fig. 11b). Above the bottom layer, the dispersal of the  
464 suspended particles present in intermediate and deep waters were advected toward the southwest by  
465 the general along slope circulation.

466  
467 *Resuspension and off-shelf sediment export induced by both waves/currents and trawls* - A simulation  
468 with both natural (waves and currents) and anthropogenic (trawling) processes was intended to check  
469 if our assumption about the independence on sediment transport was justifiable. By comparison with  
470 the sum of both processes, the annual resuspension and deposition on the shelf due to the combined  
471 effect of waves/currents and trawls decrease by ~0.17%, and the off-shelf export did not change  
472 (Table 2).

473 The resulting impact of both resuspension processes in the annual change in sediment level is  
474 depicted in figure 12. By comparison with the impact of each individual resuspension process (Fig. 7  
475 and 10), the net erosion/deposition intensity is smoothed all over the shelf. The major areas of net  
476 erosion appeared along the coast, as well as on the western outer shelf and around the Cape Creus at

477 the southwestern end of the Gulf. Net sediment accumulation took place over most in the middle shelf  
478 and eastern shelf, especially between 20 and 50 m deep.

479 In the model, trawling-induced resuspension produces over time a slight coarsening of the sediment in  
480 the fishing grounds. The impact of bottom trawling activity on the sediment grain size has been  
481 already observed elsewhere. Brown *et al.* (2005) showed on the southeastern Bering Sea that an area  
482 protected from bottom trawling, but subjected to natural resuspension as the entire coastal region  
483 area, had a significantly finer grain size owing to the lack of winnowing impact of trawling-induced  
484 resuspension. Thus some synergist effects between natural and trawling resuspensions exist, but they  
485 do not significantly change the net erosion and export fluxes for the Gulf of Lion.

486

## 487 **5. DISCUSSION**

### 488 **5.1. Comparison of sediment resuspension by waves/currents and trawls**

489 On average, the amount of sediment resuspended by waves and currents exceeds by 3 to 4 orders of  
490 magnitude those induced by trawling (Table 2). By calculating the suspended mass per bottom eroded  
491 area for annual and winter/summer periods, a comparison can be made between depths eroded by  
492 waves and currents, and by trawls (Fig. 13).

493 Wave and current resuspension flux strongly decreases with increasing water depth, because of the  
494 decreasing impact of wave motions, and stabilizes on the outer shelf where strong bottom currents still  
495 resuspend muddy sediments (Fig. 13a). Seasonal (winter and summer) fluxes in shallow water are  
496 comparable, but summer fluxes decrease more rapidly offshore due to the weaker bottom current  
497 intensity. Ulses *et al.* (this volume) and Dufois *et al.* (this volume) also demonstrate for different periods  
498 (2001 and 2003-2004 respectively) that bottom shear stress and sediment erosion was primarily  
499 controlled by waves on the inner shelf and by energetic wind-driven currents on the outer  
500 shelf.

501 Resuspension fluxes induced by trawling are maximum on the outer shelf (between 80 and 130 m of  
502 depth) and culminate around 100 m depth (Fig. 13b). Seasonally, fluxes are weaker during the winter  
503 period by a factor of about 2, because bad sea conditions reduce the average number of sea trips  
504 (Fig. 3d). On a yearly basis, resuspension fluxes generated by trawls on the outer shelf are lower than  
505 the fluxes generated at the same depths by waves and currents. However, the trawling-induced fluxes  
506 significantly exceed the waves and current-induced fluxes during summertime.

507 Churchill *et al.* (1989) suggested, using a simple model, that waves and currents on the mid-Atlantic  
508 Bight were responsible for the resuspension on the inner shelf shallow water, whereas trawling was  
509 the principal cause of resuspension on the outer shelf. Our study shows comparable results and  
510 emphasizes the significant impact of bottom trawling on sediment remobilisation in deep regions of

511 continental shelves. However, the magnitude of the trawling contribution in Churchill's work seems to  
512 be significantly greater than the present study. This can be explained by the different methods of  
513 calculation, implying a more sophisticated study in the present case. Moreover, this discrepancy very  
514 likely results from different seafloor characteristics, as the Gulf of Lion shelf is mainly made up of fine  
515 sediments (clays and silts), whereas sands primarily dominate the seafloor of the Mid-Atlantic Bight.

516

## 517 **5.2. Impact on sedimentary budget**

518 The main export pathways differ for naturally or trawling-induced resuspended sediments because of  
519 the different resuspension regions. Waves and currents resuspend sediment mostly on the inner shelf,  
520 where it is composed of coarser grains that quickly settle. The fine fraction is then primarily  
521 transported along shore toward the southwestern end of the Gulf where it escapes the shelf.  
522 Conversely, fine sediment resuspended by trawls is mostly exported to the central slope, owing to the  
523 fact that trawled regions are mainly located on the outer shelf, close to the shelf break.

524 Whereas resuspension induced by waves and currents usually dwarfs that induced by trawling, the  
525 net erosion (i.e., resuspension-deposition) and the export are more comparable (Table 2). Indeed,  
526 sediments resuspended by trawls contribute to about 5% of the annual total export of riverborne and  
527 resuspended sediment Gulf of Lion shelf (Table 2 and Fig. 5). Nevertheless, this export shows an  
528 important seasonal and interannual variability due to the storm frequency and intensity, resulting in a  
529 variable contribution of trawling to the export.

530 During summertime the effect of waves and currents is minimal while the activity of trawling is  
531 maximum. Quantitatively, these conditions induce an increased contribution of the trawling impact,  
532 which reaches 7% of the total export for the period April 1998 - September 1998. During wintertime  
533 the contribution of trawling is minimum around 4%.

534 Ulses *et al.* (submitted) estimated – using a similar modelling approach - a sediment resuspension and  
535 export by waves and currents for the Gulf of Lion for the November 2003 - May 2004 period. This  
536 latter period was characterized by large river discharges and E-SE storm activity, with the occurrence  
537 of one major flood and two extreme storms, but mild dense water formation and export. It was quite  
538 different from the low river discharges, low E-SE storm activity, but massive dense shelf water  
539 cascading 1998-1999 winter period addressed in the present study. The amount of sediment exported  
540 during comparable time period reveals that the export during the November 2003 and March 2004  
541 period ( $8.6 \times 10^6$  t) was larger than during the 1998-1999 period ( $5.7 \times 10^6$  t between November 1998 –  
542 March 1999). The 1998-1999 and 2003-2004 periods were very energetic and are believed to  
543 represent the upper range of the export. On the other side, Durrieu de Madron *et al.* (2000) estimated  
544 from a box model budgeting approach based on direct measurements performed during two seasonal  
545 surveys, an annual export of suspended particulate matter of about  $1.9 \times 10^6$  t. This crude estimate is  
546 believed to represent the lower range of the export, as surveys were performed in 1995-1996 during  
547 relatively calm conditions. Assuming that the export of sediment associated to the trawling activity is



548 relatively constant from one year to the other (i.e., of the order of  $0.4 \times 10^6$  t), we estimated that this  
549 activity could contribute between a few and 20 percents of the annual shelf-to-slope exchange of  
550 suspended sediment at the scale of the Gulf.

551

## 552 **6. CONCLUSIONS**

553 Resuspension and transport of sediment in the Gulf of Lion, due to waves and currents and to  
554 trawling, have been modelled for an annual period (April 1998 – April 1999). The major conclusions  
555 that can be drawn with these results are:

556 - Natural resuspension by waves and currents occurred during short episodes mostly during fall and  
557 winter. It was concentrated on the inner-shelf due to wave action, but also on the southwestern  
558 outer shelf due to the strong bottom currents occurring during wintertime. Trawling-induced  
559 resuspension occurred regularly throughout the year. It was concentrated on the outer shelf, with a  
560 maximum intensity around 90 m depth. Trawling-induced resuspension fluxes are on average  
561 several orders of magnitude lower than the waves and currents-induced resuspension fluxes.  
562 Nevertheless, they are maximum and locally predominant during summertime when the wave and  
563 currents activity is lowest.

564 - The total annual off-shelf export of sediment by waves and currents were one order of magnitude  
565 larger than the export linked to trawling. Export concerned the finest fraction of the sediment (clays  
566 and fine silts) and took place primarily in the southwestern end of the Gulf for the sediment  
567 resuspended by waves and currents and the central shelf for the sediment resuspended by  
568 trawling. During energetic years (i.e., with large flood, strong marine storm or dense water  
569 formation), the trawling activity contributed little (few percents) to the total shelf export of fine  
570 sediment. However, trawling was thought to contribute significantly (up to 20% of the export)  
571 during calm years.

572 - No significant interferences between both resuspension processes were estimated in term of  
573 resuspension/deposition and export fluxes.

574 Because of the site-specific characteristics of natural resuspension and transport mechanisms,  
575 morphological and sedimentological settings, intensity and distribution of the trawling effort, all the  
576 conclusions obtained for the Gulf of Lion may not necessarily apply to other continental shelves.  
577 Nevertheless, the depth limitation of resuspension by waves and the increasing impact of trawling in  
578 deeper portions of the shelf - while natural resuspension processes become tenuous - are likely to be  
579 features common to most coastal regions with significant bottom trawling activity.

580

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585

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- 753

754 **APPENDIX 1**

755 *Suspended sediment transport equation*

756 The advection-diffusion equation is based on the mass conservation of the suspended sediment

$$\frac{\partial C^i}{\partial t} + u \frac{\partial C^i}{\partial x} + v \frac{\partial C^i}{\partial y} + (w - W_s^i) \frac{\partial C^i}{\partial z} = K_z \frac{\partial^2 C^i}{\partial z^2} \quad (1)$$

757 where  $C^i$  is the suspended sediment concentration (SSC) for the  $i^{\text{th}}$  class of particles,  $W_s^i$  is the settling  
758 velocity,  $u$ ,  $v$  and  $w$  are the horizontal and vertical velocity respectively and  $K_z$  is the vertical diffusion  
759 coefficient.

760

761 The vertical turbulence was estimated using a turbulent closure scheme where the vertical diffusion

762 coefficient  $K_z$  is derived from the local Richardson number  $\left( Ri = -\frac{(g/\rho)(\partial\rho/\partial z)}{(\partial u/\partial z)^2} \right)$ :

$$K_z = 1.67 \times 10^{-3} \left( 1 + \frac{10}{3} Ri \right)^{-3/2} \quad (2)$$

763 where  $\rho$  is the water density and  $g$  is the gravitational acceleration equal to  $9.81 \text{ m}^2 \text{ s}^{-1}$ .

764

765 Settling velocity  $W_s^i$  (in  $\text{m s}^{-1}$ ) for the particles with a diameter lower than  $100 \mu\text{m}$  was estimated as the  
766 mean Stokes velocity of the individual size bins  $D_j$  (in  $\text{m}$ ):

$$W_s^i = \frac{(s_i - 1)gD_i^2}{18\nu} \quad (3)$$

767 where  $s_i$  is the relative grain density and  $\nu$  is the kinematic water viscosity equal to  $1.14 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ .

768 Settling velocity for sand grain coarser than  $100 \mu\text{m}$  is computed using Zanke (1977) formula:

$$W_s^i = \frac{10\nu}{D_i} \left\{ \left[ 1 + \frac{0.01(s_i - 1)gD_i^3}{\nu^2} \right]^{0.5} - 1 \right\} \quad (4)$$

769

770 Settling velocity of aggregates is computed using the relationship from Agrawal and Pottsmith (2000):

$$W_s^i = 0.45 \times 10^{-3} (D_i / 2)^{1.17} \quad (5)$$

771 where  $W_s^i$  and  $D_i$  are expressed in  $\text{cm s}^{-1}$  and  $\mu\text{m}$  respectively.

772

773 Density of primary particles is taken as the mineral grain density ( $2640 \text{ kg m}^{-3}$ ) and density of  
774 aggregates is calculated according to Hill *et al.* (1998):

$$\rho_f^i = \rho + \frac{18\mu W_s}{gD_f^2} \left( 1 + \frac{3C}{16} \text{Re} \right) \quad (6)$$

775 where  $\rho_f^i$  is the aggregate density,  $\mu$  is the dynamic water viscosity ( $1.14 \times 10^{-3} \text{ kg m}^{-1} \text{ s}^{-2}$ ),  $W_s$  is the  
776 aggregate settling velocity,  $D_f$  is the aggregate diameter,  $C$  is the Carrier coefficient (0.43) and  
777  $\text{Re} = \rho W_s^i D_f^i / \mu$  is the class  $i$  Reynolds number.

778

779 **APPENDIX 2**

780 *Erosion flux for trawl*

781 The fluxes of sediment resuspended by bottom trawls were estimated experimentally and presented in  
 782 Durrieu de Madron *et al.* (2005). By comparing resuspension by two different configurations of  
 783 groundrope gear (chain or “rock hopper” fixed rubber discs), working at a speed of 3 knots over the  
 784 ground, with an average net aperture and door width of 16 m, they showed that resuspension by trawl  
 785 depend on the trawl's groundrope, but above all on the sediment texture (clay content). A linear  
 786 relationship is inferred between the total resuspension flux,  $E_T$  in  $\text{kg m}^{-2} \text{s}^{-1}$ , and the clay fraction,  $F_C$  in  
 787 %:

$$E_T = 0.011 F_C + 0.47 \quad (r^2 = 0.74)$$

788 Total flux is then fractionated for the different sediment grain sizes, according to the fraction  $p_i$  of class  
 789  $i$ .

$$F^i = p_i E_T$$

790

791 *Erosion fluxes for waves and currents*

792 *Partheniades' law for cohesive sediments* - It permits to calculate the erosion flux  $F$  for each particle  
 793 class  $i$  according to the relation:

$$F^i = p_i E_0^i \left( \frac{\tau_{\max,s}}{\tau_{cr_i}} - 1 \right) \text{ if } \tau_{\max,s} \geq \tau_{cr_i} \quad (7)$$

794 where  $\tau_{cr_i}$  is the critical shear stress for the class  $i$  and  $p_i$  is the fraction of class  $i$ . The erosion  
 795 coefficient  $E_0$  depends on the physico-chemical sediment characteristics and ranged between  $10^{-5}$   
 796 and  $2 \cdot 10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}$  (Mulder et Udink, 1991; Amos *et al.*, 1992; Amos *et al.*, 1997, Widdows *et al.*,  
 797 1998). In this study, the coefficient  $E_0$  was set to  $1 \cdot 10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$

798

799 *Reference concentration method for non-cohesive sediments* – It permits to calculate the erosion flux  
 800  $F$  for each particle class  $i$  according to the relation:



$$F^i = p_i W_s^i C(z_1) \rho_s^i \quad (8)$$

801 where  $C(z_1)$  is an adimensional concentration at the height  $z_1$  corresponding to the first layer of the  
 802 grid of above the seabed. Under combined wave and currents conditions, sediment is resuspended  
 803 within the wave boundary layer and diffused in the water column by turbulence associated with the  
 804 current (Soulsby *et al.*, 1993). In the model, height of the first layer ( $z_1$ ) is variable and can be above  
 805 the wave boundary layer of thickness  $z_w$ . The concentration  $C(z_1)$  is thus calculated according to the  
 806 reference concentration  $C_a$ , at height  $z_a=2D_{50}$ , or the concentration at the boundary layer level  $C(z_w)$ .

$$C(z_1) = C_a \left( \frac{z_1}{z_a} \right)^{-b_{\max}} \quad \text{for } z_a \leq z_1 \leq z_w \quad \text{with } b_{\max} = \frac{W_s}{\kappa u_{* \max}} \quad \text{and } b_m = \frac{W_s}{\kappa u_{* m}}$$

$$C(z_1) = C(z_w) \left( \frac{z_1}{z_w} \right)^{-b_m} \quad \text{for } z_w < z_1 \quad z_w = \frac{u_{* \max} T}{2\pi} = \text{wave boundary thickness}$$

807  $W_s$  is the sediment settling velocity,  $\kappa$  is the von Karman constant ( $= 0.40$ ),  $u_{* \max} = (\tau_{\max} / \rho)^{1/2}$ ,  $u_{* m} = (\tau_m$   
 808  $/ \rho)^{1/2}$ ,  $\tau_{\max}$  is the maximum bed shear-stress in wave cycle,  $\tau_m$  is the mean bed shear-stress in wave  
 809 cycle, and  $T$  the wave period.

810 The determination of the reference concentration is based on Zyserman and Fredsøe (1994) method,  
 811 and is calculated for a grain-related roughness height of  $2.5 \times D_{50}/30$ :

$$C_a = \frac{0.331 (\theta_{\max, s} - 0.045)^{1.75}}{1 + 0.720 (\theta_{\max, s} - 0.045)^{1.75}} \quad (9)$$

812 Where  $\theta_{\max, s} = \frac{\tau_{\max, s}}{g(\rho_s - \rho)D_{50}}$  is the skin-friction Shields parameter.

813 The latter method is designed for flat-bed condition, so that  $\tau_{\max}$  and  $\tau_m$  are calculated using a grain  
 814 related roughness height ( $2.5 \times D_{50}/30$ ). For a rippled bed, total-stress values should be used.

815

### 816 *Critical shear stress*

817 The critical shear stress is the shear stress from which sediment is likely to be removed. It depends on  
 818 the grain itself and on bottom characteristics. This value is difficult to establish because it can vary  
 819 from a factor 10 to 20 according to the type of resuspension considered.

820 For coarse non-cohesive sediments which mainly depend on grain characteristics, critical shear stress  
 821 of each class  $i$  is given in form of a critical Shields parameter value  $\theta_{cr}^i$  which depends on

822 adimensional grain size and results from experiments. Soulsby and Whitouse (1997) determined an  
 823 algebraic equation nearest to the Shields curve:

$$\theta_{cr}^i = \frac{0.30}{1+1.2D_*^i} + 0.055 \left[ 1 - e^{-0.020D_*^i} \right] \text{ where } D_*^i = \left[ \frac{g(s^i - 1)}{\nu^2} \right]^{1/3} D_{50}^i \quad (10)$$

824 Critical shear stress  $\tau_{cr}^i$  is thus calculated with the equation

$$\theta_{cr}^i = \frac{\tau_{cr}^i}{g(\rho_s^i - \rho)D_{50}^i} \quad (11)$$

825

826 *Roughness and bedforms*

827 For non-cohesive sediments, total bottom roughness is computed using the relationship

$$z_0 = k/30 \quad (12)$$

828 where  $k$  is the total roughness height, and is the sum of three components: grain-related component  
 829 ( $k_g$ ), bedload component ( $k_t$ ), and form-drag component ( $k_f$ ) (Grant and Madsen, 1982).

$$k = k_g + k_t + k_f \quad (13)$$

830 Grain roughness height is calculated using:

$$k_g = 2.5 \times D_{50} \quad (14)$$

831 Bedload roughness is calculated using:

$$k_t = 522 \times D_{50} (\theta_{cws} - \theta_{cr})^{0.75} \quad (15)$$

832 where  $\theta_{cws} = \rho u_{cws}^2 / (\rho_s - \rho) g D_{50}$  is the Shields parameter related to the skin roughness,  $\theta_{cr}$  is the  
 833 critical Shields parameter which define grains remobilization, and  $U_{cws}$  is combined wave and currents  
 834 shear velocities.

835 The ripple height and wavelength is then calculated according to Li and Amos (1998) (see below) to  
 836 obtain the form drag roughness height

837

$$k_f = a_r \eta^2 / \lambda \quad (16)$$

838 where  $a_r$  is a coefficient which varies according to authors. We choose 27.7, the most common value,  
839 fixed by Grant and Madsen (1982).

840 The ripple height and wavelength depend on the characteristic and hydrodynamical conditions. Skin  
841 shear velocities ( $u_{cws}^*$ ) and skin-friction combined wave and current Shields parameter ( $\theta_{cws}$ ) are first  
842 calculated using the grain roughness height  $k_g$ . The bedload roughness  $k_r$  can thus be calculated, and  
843 is used to obtain bedload shear velocities ( $u_{wt}^*$ ,  $u_{ct}^*$ ,  $u_{cwt}^*$ ). To calculate ripples dimension, the  
844 combined-flow ripple predictor proposed by Li and Amos (1998), based on their filed observations of  
845 ripples on Scotian Shelf, is used. Ripple dimensions are calculated according to five limit condition for  
846 friction velocities: ripple-enhanced shear velocity ( $u_{cwe}^*$ , Nielsen, 1986), critical shear velocity for  
847 bedload transport ( $u_{cr}^*$ ), critical shear velocity for ripple break-off ( $u_{bf}^*$ , Grant and Madsen, 1982) and  
848 critical shear velocity for upper-plane bed sheet-flow ( $u_{up}^*$ ). This last variable is given from a data  
849 compilation from preceding studies, carried out by Li and Amos (1998).

850  $u_{cwe}^* = u_{cws}^* / (1 - \pi \eta_p / \lambda_p)$  where  $\eta_p$  and  $\lambda_p$  are respectively height and wavelength of pre-existing  
851 ripples.

852  $u_{cr}^* = \sqrt{\tau_{cr} / \rho}$ ,  $\tau_{cr}$  being the critical shear stress for erosion as explain hereafter.

853  $u_{bf}^* = 1.34 S_*^{0.3} u_{cr}^*$  where  $S_* = (D_{50} / 4\nu) [(\rho_s - \rho) g D_{50} / \rho]$  is without dimension and  $\nu$  is the  
854 cinematic seawater viscosity (equal to  $1.14 \times 10^{-6}$  for a 15°C seawater).

855  $u_{up}^* = \sqrt{\tau_{up} / \rho}$  where  $\tau_{up} = \theta_{up} (\rho_s - \rho) g D_{50}$  and  $\theta_{up} = 0.172 D_{50}^{-0.376}$ ,  $D_{50}$  is expressed in mm.

856 The five limit conditions are presented above and permit to determine the adapted equations to  
857 calculate ripples height  $\eta_{rip}$  and wavelength  $\lambda_{rip}$  :

858 - If  $u_{cwe}^* < u_{cr}^*$ , there is no sediment transport and ripples have the same dimension as precedent time  
859 step.

860 - If  $u_{cwe}^* > u_{cr}^*$  and  $u_{cws}^* < u_{cr}^*$ , the transport is local, weak, and close to ripples crest.

861 •  $\eta_{rip} / D_{50} = 19.59 (u_{cws}^* / u_{cr}^*) + 20.92$

862 •  $\eta_{rip} / \lambda_{rip} = 0.12$

863 - If  $u_{cws}^* > u_{cr}^*$  and  $u_{cwt}^* < u_{bf}^*$ , overall bedload transport will occur.

864 case n°1 :  $u_{cw}^* / u_{cs}^* \geq 1.25$ , wave-dominant ripples

865 ○  $\eta_{rip} / D_{50} = 27.14 (u_{cwt}^* / u_{cr}^*) + 16.36$

866 ○  $\eta_{rip} / \lambda_{rip} = 0.12$

867 case n°2 :  $u_{cw}^* / u_{cs}^* < 1.25$ , current-dominant ripples or interaction between wave and currents

868 ○  $\eta_{rip} / D_{50} = 22.15 (u_{cwt}^* / u_{cr}^*) + 6.38$

869  $\circ \quad \eta_{rip} / \lambda_{rip} = 0.12$

870 - If  $u^{*bf} \leq u^{*cwt} < u^{*up}$ , break-off ripples will form

871 -  $\lambda_{rip} = 535 D_{50}$

872 -  $\eta_{rip} / \lambda_{rip} = 0.15 (u^{*up} - u^{*cwt}) / (u^{*up} - u^{*bf})$

873 - If  $u^{*cwt} \geq u^{*up}$ , ripples are washed out and upper-plane bed will be predicted.

874 -  $\eta_{rip} = 0$

875 -  $\lambda_{rip} = 0$

876 From these ripples height and wavelength values, the drag roughness, and then the total bottom  
877 roughness can be calculated, giving access to the calculation of the bottom shear stress which will  
878 determine the reference concentration.

879

880 For cohesive sediment, biological activity can have a considerable effect on bottom roughness.  
881 Microbial exudates can increase the critical shear stress, and presence of burrows in the sediment,  
882 due to bioturbation, can strengthen the seabed (Meadows *et al.*, 1990; Black, 1997). Data concerning  
883 biological roughness being non-existent in the Gulf of Lion, ripples height and the wavelength for  
884 3.6cohesive sediment are selected here equal to those measured on a silty site in the North-East of  
885 California, that says 0.6 cm and 10 cm respectively (Wheatcroft, 1994). The steepness of biogenic  
886 roughness elements is assumed to decay under high shear stresses as:

$$\frac{\eta_{bio}}{\lambda_{bio}} = \exp(-1.67 \ln \theta_w - 4.11) \quad (\text{Harris and Wiberg, 2001}) \quad (17)$$

887 where  $\theta_w = \tau_{*w} / g(\rho_s - \rho)D_{50}$ .

888 For mixed sediment, an average between silty-bed and sandy-bed roughness scale is used, weighted  
889 by sand fraction of the bed (Harris et Wiberg, 2001) :

$$\begin{aligned} \eta &= \eta_{rip} f_{rs} + \eta_{bio} (1 - f_{rs}) \\ \lambda &= \lambda_{rip} f_{rs} + \lambda_{bio} (1 - f_{rs}) \end{aligned} \quad (18)$$

890 where  $f_{rs}$  is the sandy fraction. In the same way, total roughness is calculated by weighted average of  
891 the cohesive and non-cohesive contributions. A minimum value of  $z_0=0.005$  cm is specified so that  
892 roughness estimates do not become too small given the small-scale bed variations generally present  
893 on the sea floor.

894

895 *Bed armoring*

896 We used the method of Harris and Wiberg (2001), which considers several layers below an active  
897 layer available for erosion. Underlying layers are only available when active layer gets thinner by  
898 erosion or when shear stress increases. At the initial time, all layers (under-layers and active layer)  
899 have the same particle size distribution. The thickness and particle size distribution of each layer are  
900 updated at each time step according to deposit and erosion. Volume of each particles class per unit  
901 area of eroded seabed during a time step is limited by the quantity of sediment available in the active  
902 layer.

903 The active layer of sandy bottom ( $\delta^{rip}$ ) is calculated according to the migration rate of the bottom ( $Q_b$ )  
904 and the size of the ripples  $\eta_{rip}$  and  $\lambda_{rip}$  during a half wave-period:

$$\delta^{rip} = \frac{Q_b T}{2C_b \lambda_{rip}} + 6D_{50} \quad (19)$$

where  $Q_b = \sum_i \left[ fr_i \frac{25.3}{(\rho_s^i - \rho) g} (\tau_{cws} - \tau_{cr}^i)^{1.5} \right]$  and  $\tau_{cws} = \rho u_{*cws}^2$

905 where  $fr_i$  is the fraction of class  $i$  present in the sediment,  $C_b$  is the concentration of the sediment (1-  
906 porosity), and  $6D_{50}$  represents irregularities due to grains in order to prevent the active layer to  
907 disappear when no transport occurs.

908 For silty sediments, the active layer depth is supposed to be proportional to the shear stress at the  
909 bottom compared to the critical shear stresses  $\tau_{cr(50)}$  of the sediment.

$$\delta^{silt} = 0.006 (\tau_{cws} - \tau_{cr(50)}) + 6D_{50} \quad (20)$$

910

911 For mixed sediment (mixture of silt and sand), the mixed layer  $\delta_{mix}$  is calculated as a weighted mean of  
912 active layer depths for sandy and silty sediments.

$$\delta_{mix} = \delta^{rip} fr_s + \delta^{silt} (1 - fr_s) \quad (21)$$

913 where  $fr_s$  is the sand fraction of the bed. Volume of sediment available for erosion in a size class  $i$  per  
914 unit area of the bed is  $fr_i C_b \delta_{mix}$ . This volume is used to limit the erosion, taking into account initial  
915 sediment characteristics (critical shear stress for erosion, grain density and particle size distribution).  
916 Hence, when erosion exceeded the available sediment volume for each class  $i$  at a given site, bed  
917 armoring is applied by reducing the flux of this class.

918 **FIGURES CAPTIONS**

919 Figure 1. (a) Bathymetry of the Gulf of Lion in the model and position of hydrological stations. The  
920 thick dashed line around the shelf break depth (200 m) delineates the limit between the shelf and the  
921 open sea. Stars near the coast and within canyon heads represent the location of the bottom-shear  
922 stress estimates (Fig. 3e) and near-bottom density anomaly estimates (Fig. 3 f). The shelf is  
923 subdivided in two halves (cross shelf thin dashed line) for water flux estimates given in Fig. 3g. (b)  
924 Median grain size of superficial sediment showing the seaward fining texture of the sediment and  
925 coarsening around the shelf edge.

926 Figure 2. Probability density distribution of bottom trawls for a) weak wind ( $\leq 10 \text{ m s}^{-1}$ ) and b) strong  
927 winds ( $>10 \text{ m s}^{-1}$ ). Black dots indicate the position of fishing ports sheltering the fleet of bottom  
928 trawlers: PV (Port-Vendres), PN (Port-la-Nouvelle), A (Agde), S (Sète), GR (Grau du Roi), PB (Port de  
929 Bouc). Isobaths 50, 200, 1000 and 2000 m superimposed as black lines.

930 Figure 3. Time series from April 1998 to April 1999 of (a) water discharges from the Rhône River and  
931 other rivers of the Gulf of Lion, (b) solid discharge from all rivers, (c) wind off Sète, (d) daily strength of  
932 bottom trawls in the Gulf of Lion, (e) bottom shear stress off Marseille and Banyuls (see Fig. 1 for  
933 position), (f) water density anomaly at 200 m depth at the eastern end (Planier Canyon) and  
934 southwestern end (Cape Creus Canyon) of the Gulf, and (g) and water flux across the shelf break  
935 (slope water import onto the shelf is positive, whereas shelf water export is negative).

936 Figure 4. Map of sediment thickness accumulated after a 16-month simulation (January 4, 1998 –  
937 March, 31, 1999) taking solely into account sediment discharges from rivers (no resuspension  
938 allowed).

939 Figure 5. Cumulative export (in  $10^6$  Tons) for the different scenarios: a) natural (waves and currents),  
940 b) trawls and c) mixed (waves, currents, and trawls). The dotted line indicates the sum of export for  
941 scenarios (a) and (b).

942 Figure 6. Annual (from April 1, 1998 to March 31, 1999) variability of the mass of sediment  
943 resuspended daily by waves and currents on the shelf (a) and exported towards the slope (b).

944 Figure 7. Map of sediment thickness accumulated or eroded between April 1, 1998 and March 31,  
945 1999 taking into account sediment discharges from all rivers and resuspension by waves and currents.  
946 The contours are in mm, positive values (light areas) represent deposition and negative values (dark  
947 areas) represent erosion.

948 Figure 8. Cross-margin sections on the western part of the Gulf of Lion (see Fig. 1 for section position)  
949 showing the distribution of suspended sediment concentration, resuspended by waves and currents,  
950 along with water density anomaly in (a) strongly stratified conditions (27 September 1998), and (b)

951 weakly stratified conditions (24 February 1999). The contour unit is  $\text{mg L}^{-1}$ . The inserted map indicates  
952 the location of the cross-slope transect.

953 Figure 9. Annual (from April 1, 1998 to March 31, 1999) variability of the mass of sediment  
954 resuspended daily by bottom trawlers on the shelf (a) and exported towards the slope (b). Trawling  
955 activity occurs every day but during weekends and holidays.

956 Figure 10. Map of sediment thickness accumulated or eroded between April 1, 1998 and March 31,  
957 1999 taking into account sediment discharges from all rivers and resuspension by bottom trawling.  
958 The contours are in mm, positive values (light areas) represent deposition and negative values (dark  
959 areas) represent erosion.

960 Figure 11. Cross-margin sections on the western part of the Gulf of Lion (see Fig. 1 for section  
961 position) showing the distribution of sediment concentration, resuspended by bottom trawling, along  
962 with water density anomaly in (a) strongly stratified conditions of the upper layer of the water column  
963 (27 September 1998), and (b) weakly stratified conditions (24 February 1999). The contour unit is  $\text{mg}$   
964  $\text{L}^{-1}$ . The inserted map indicates the location of the cross-slope transect.

965 Figure 12. Annual and seasonal variation with depth of the temporally integrated resuspension fluxes  
966 on the Gulf of Lion's shelf linked (a) to natural (wave and current) activity, and (b) to bottom trawling  
967 activity. The first 30 m depths are not represented because of the strong erosion by waves and  
968 currents very near the coast which dwarfed the other values.

969 Figure 13. Map of sediment thickness accumulated or eroded between April 1, 1998 and March 31,  
970 1999 taking into account sediment discharges from all rivers and both resuspension by waves and  
971 currents, and bottom trawling. The contours are in mm, positive values (light areas) represent  
972 deposition and negative values (dark areas) represent erosion.

### 973 **TABLE CAPTIONS**

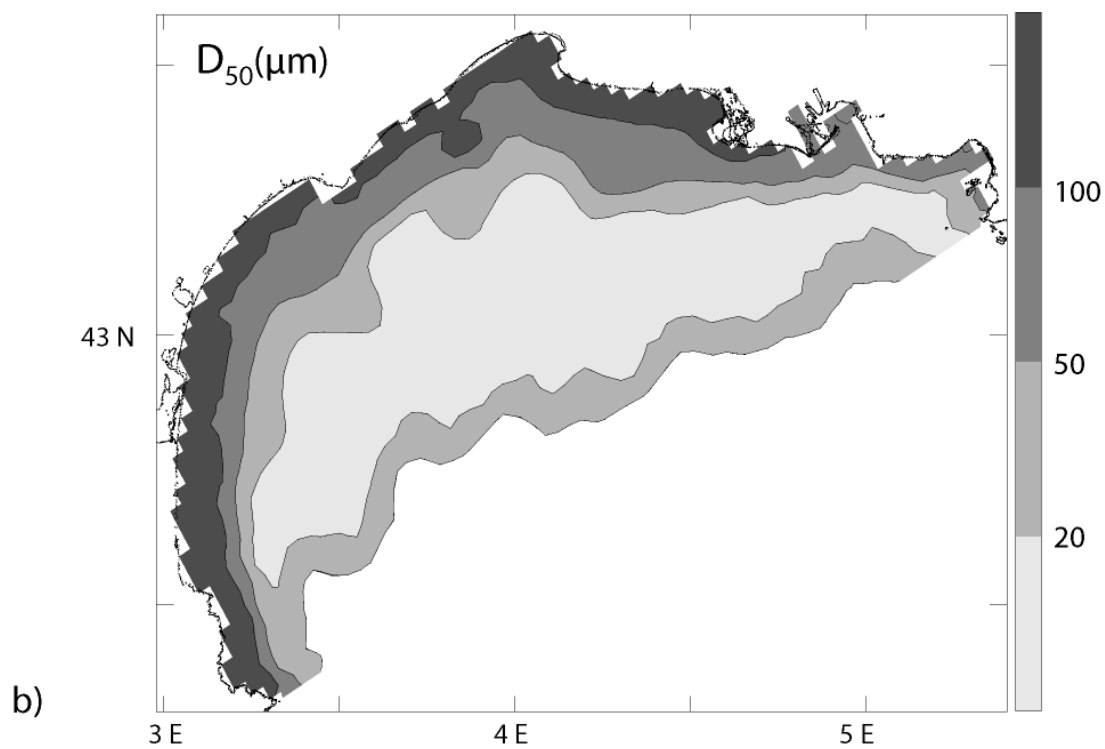
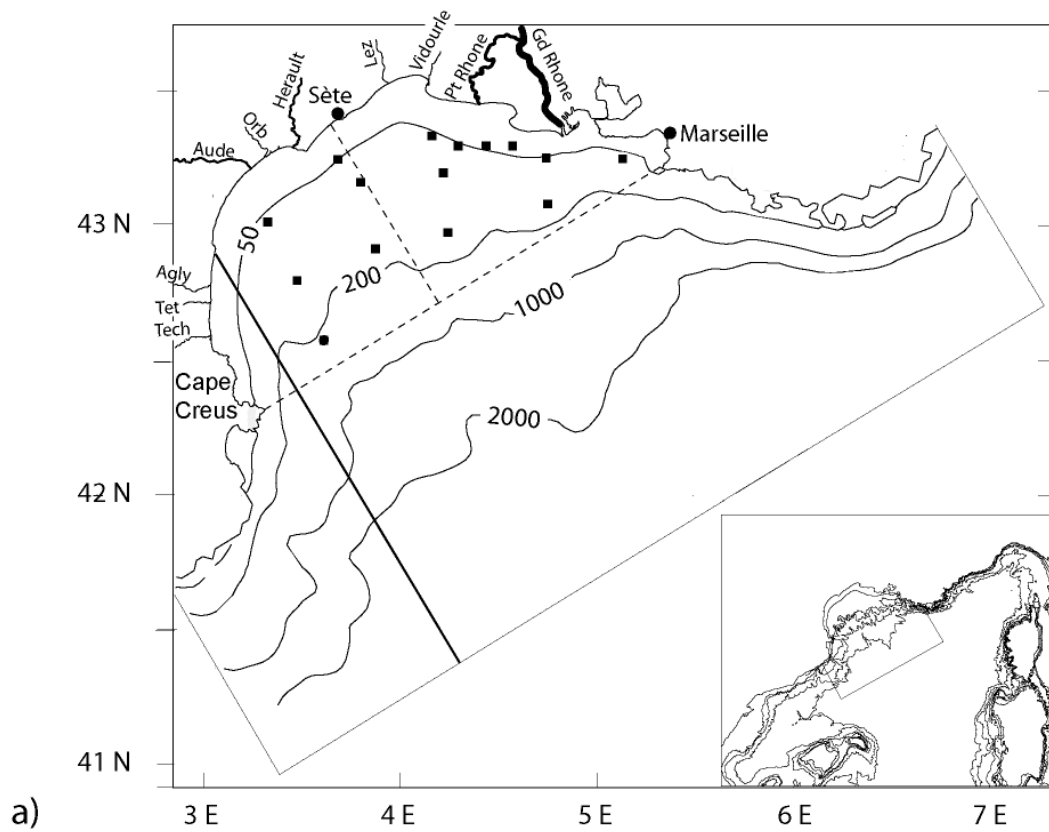
974 Table 1. Characteristics of particle grain size classes used in the sediment transport model.

975 Table 2. Annual sediment fluxes integrated between April 1, 1998 and March 31, 1999. Scenarios with  
976 natural (waves and currents) and/or trawling resuspension include sediment input by rivers. Deposition  
977 and export rates for these scenarios exclude the deposited and exported sediment directly deriving  
978 from rivers. Once riverine sediment has been deposited on the shelf it is accounted in the  
979 resuspension, and subsequent deposition and export fluxes.

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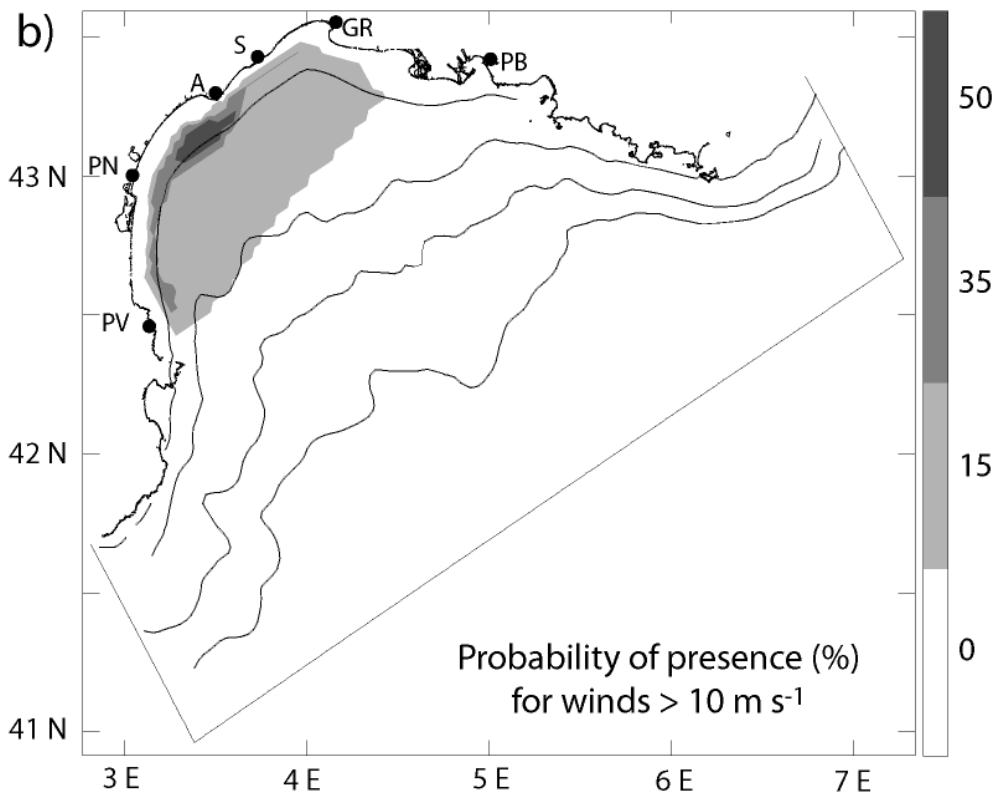
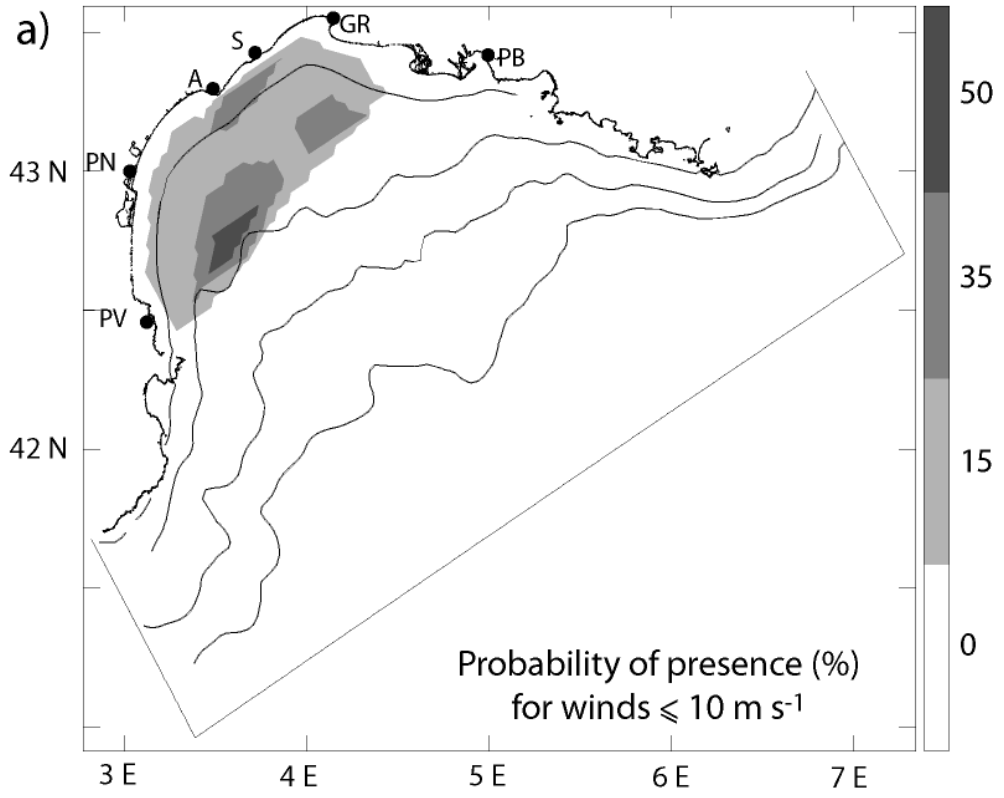


Ferre et al. Figure 1

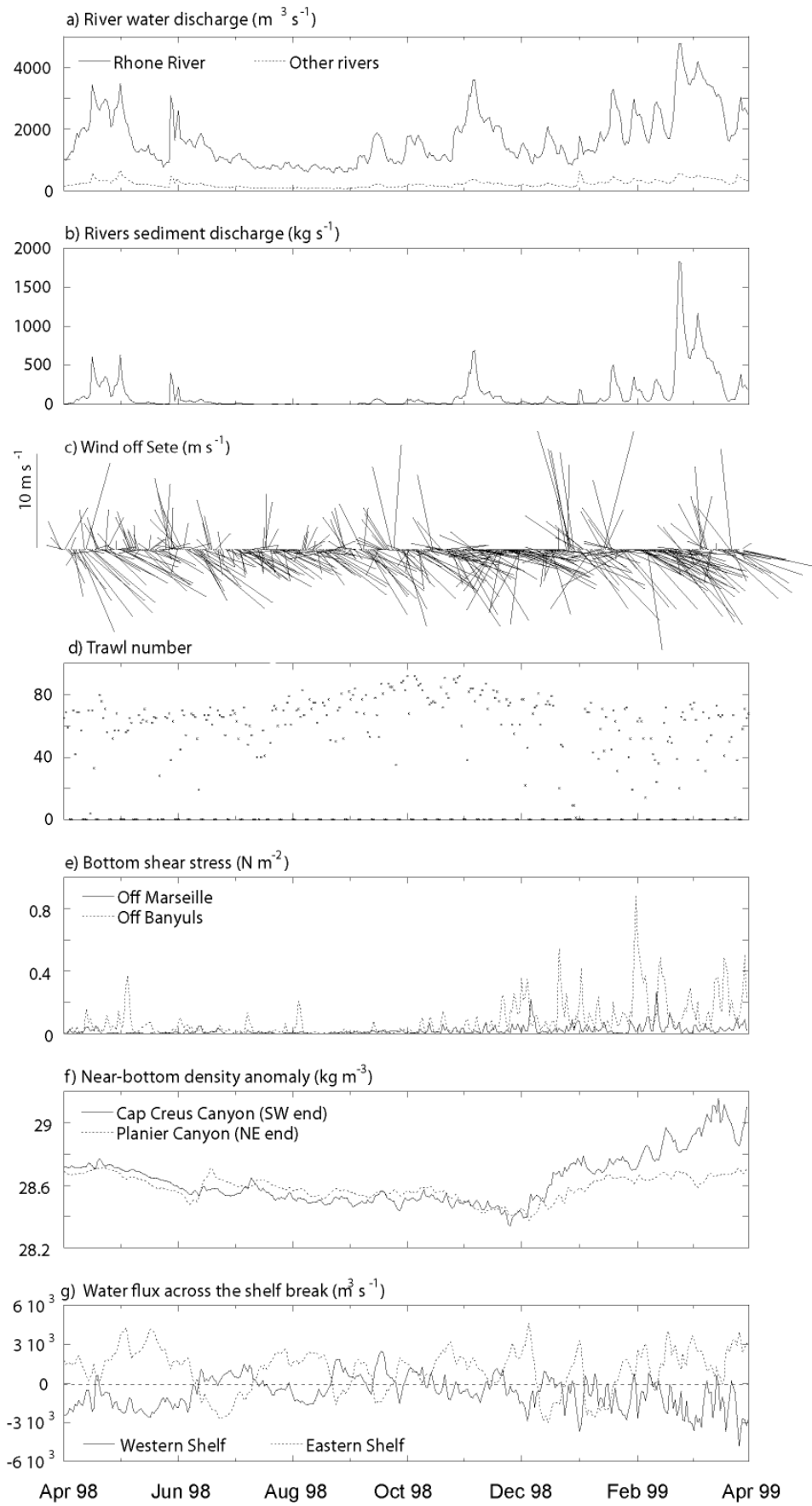
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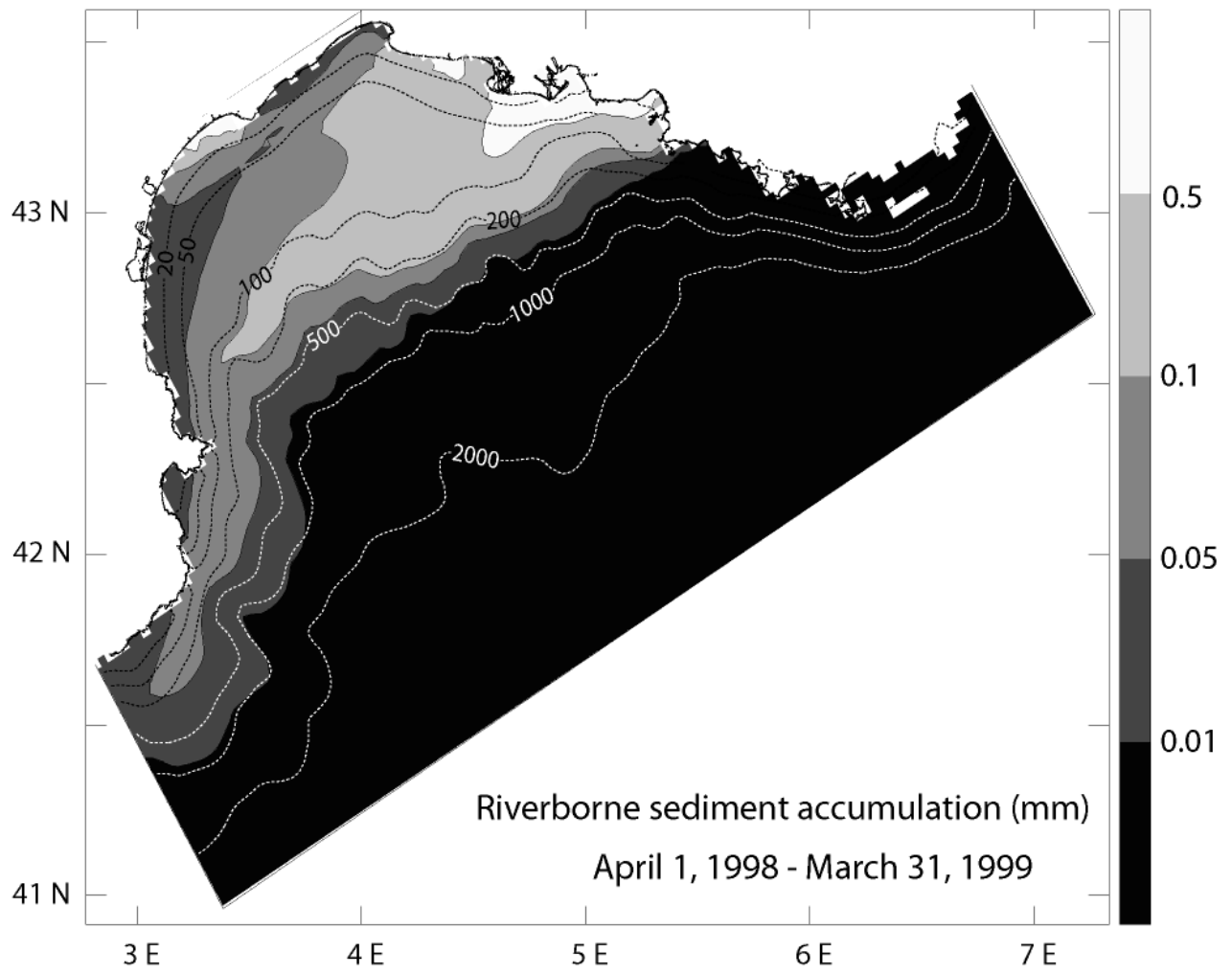
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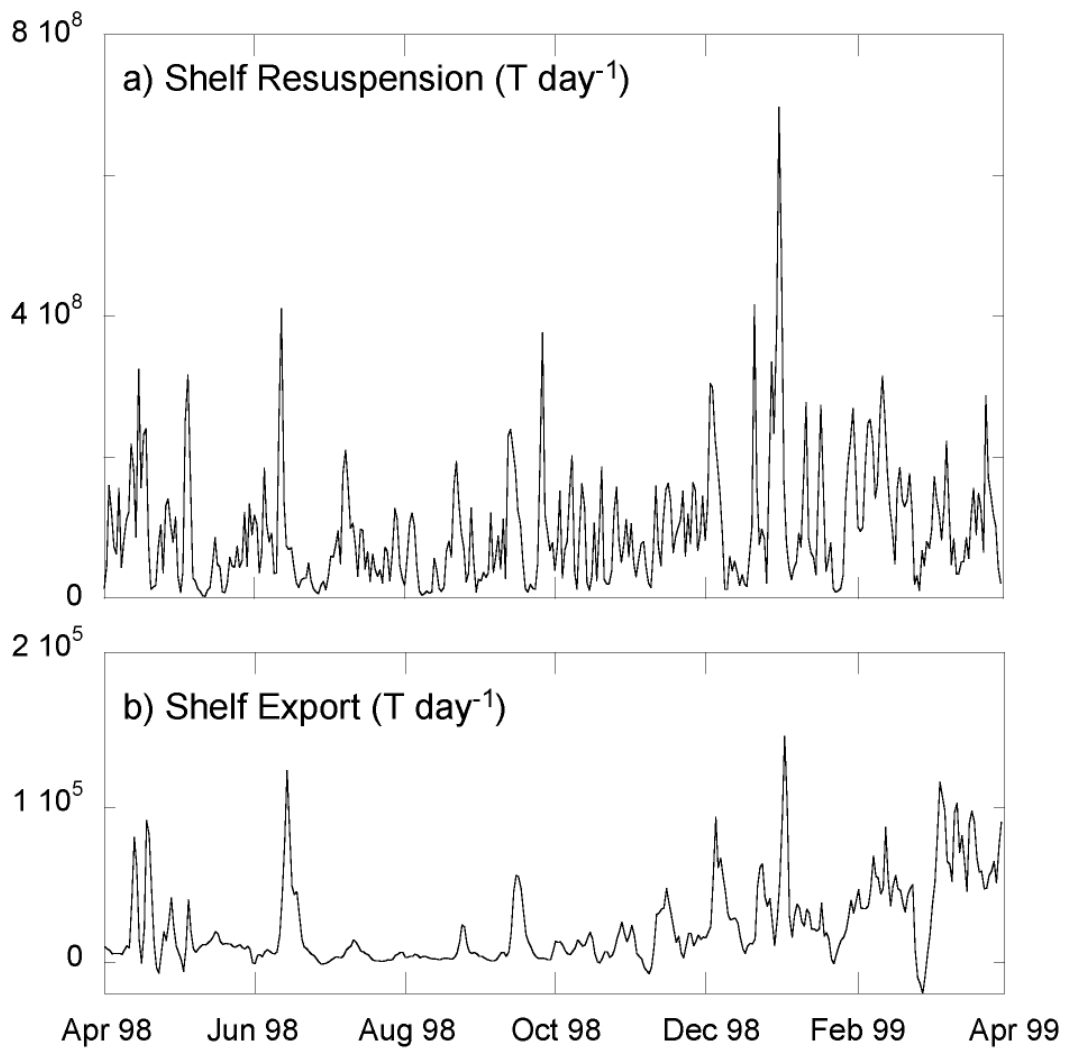


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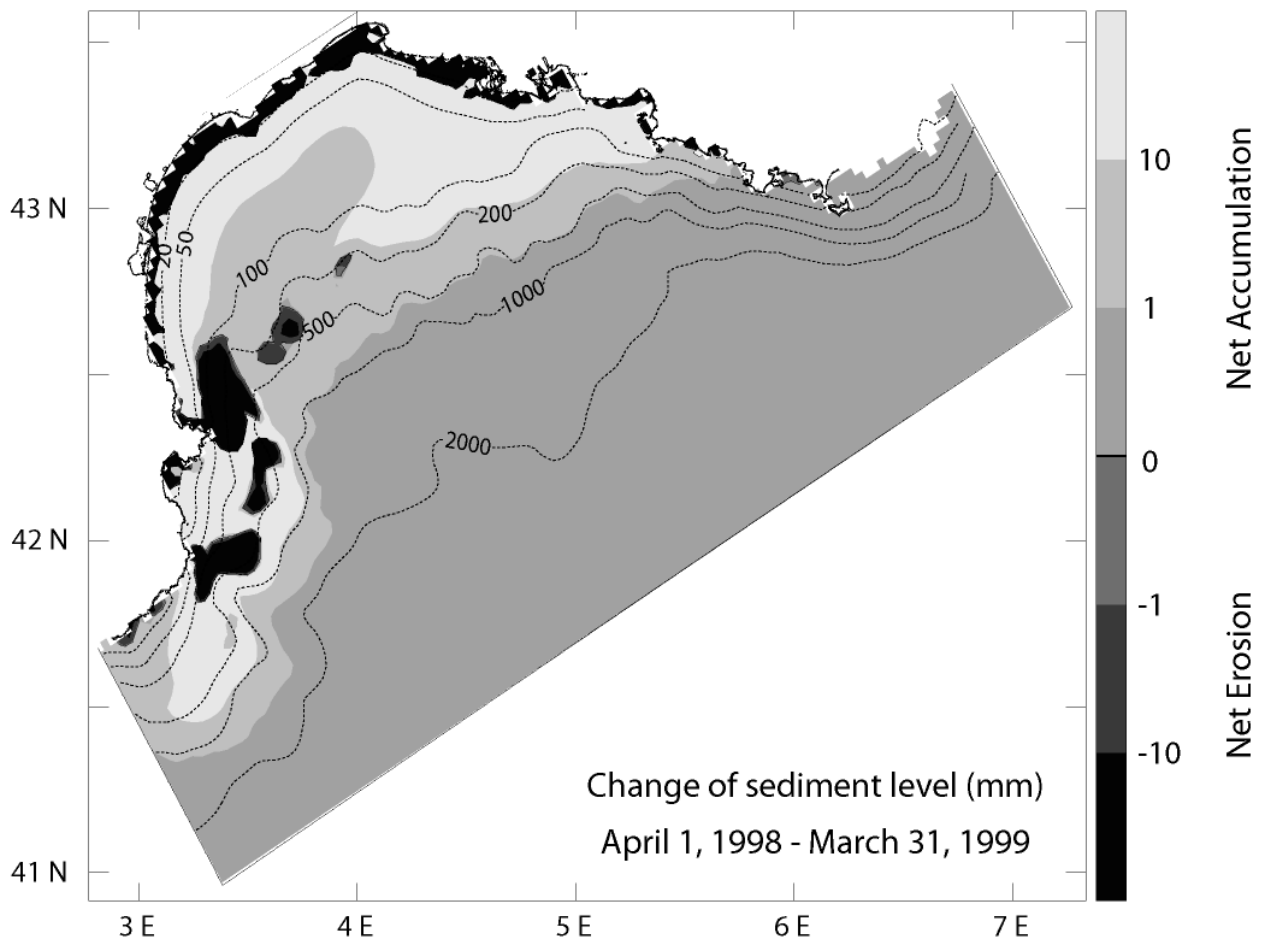
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Ferre et al. Figure 5

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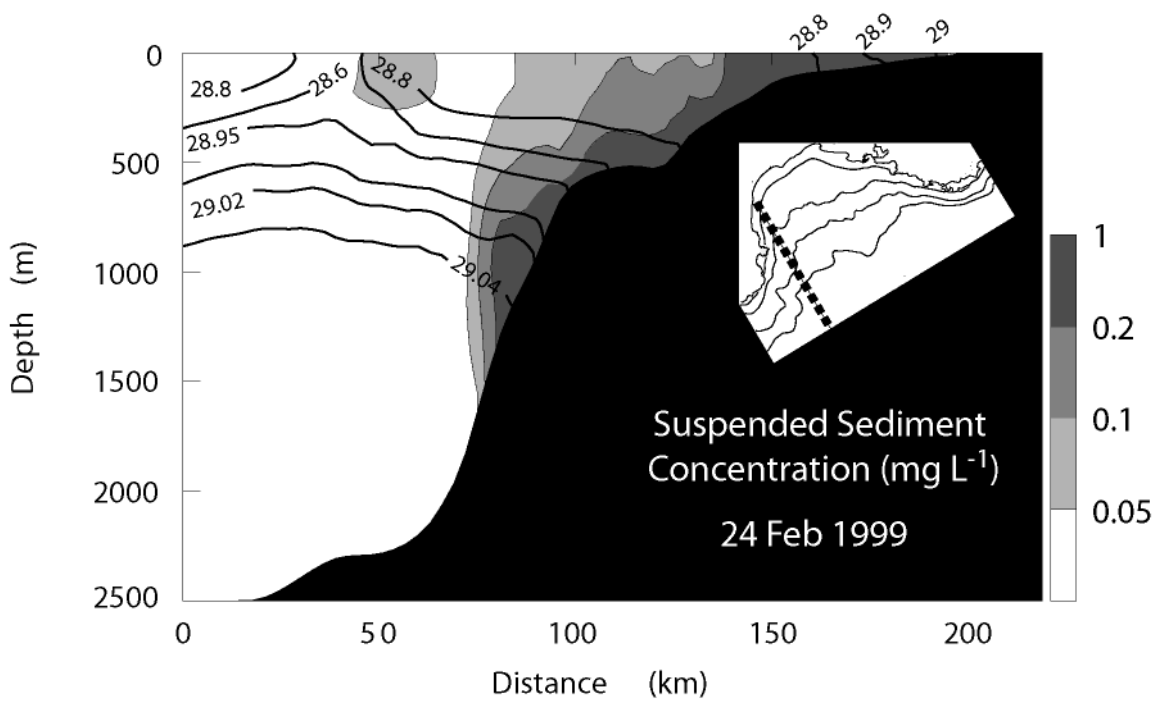
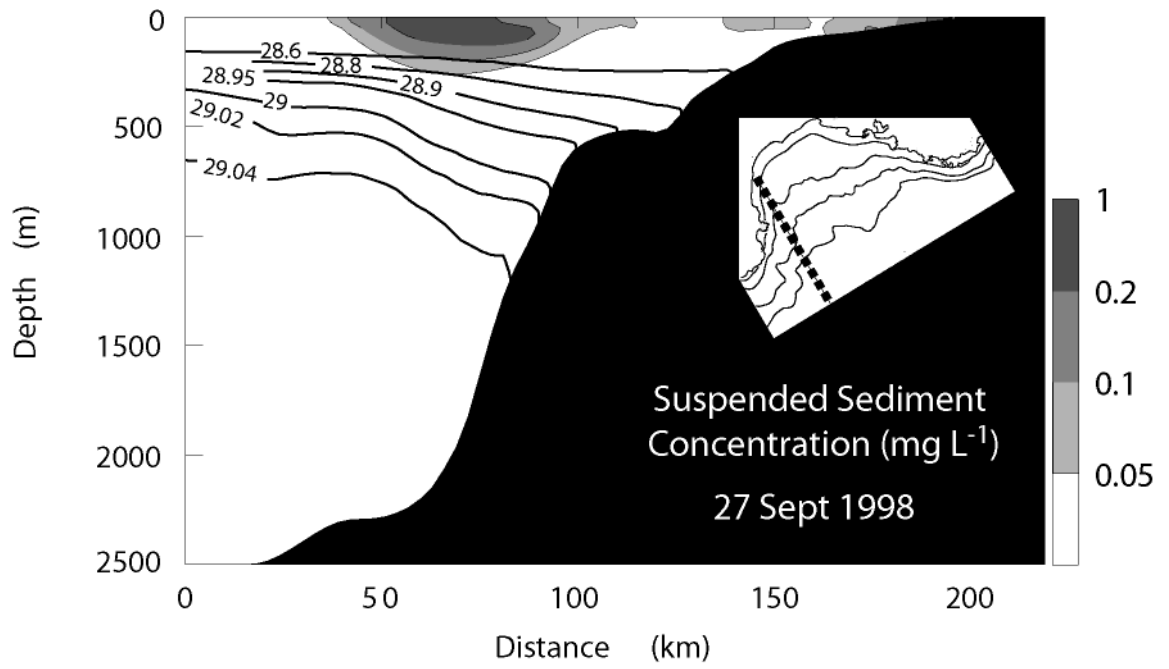
Ferre et al. Figure 6



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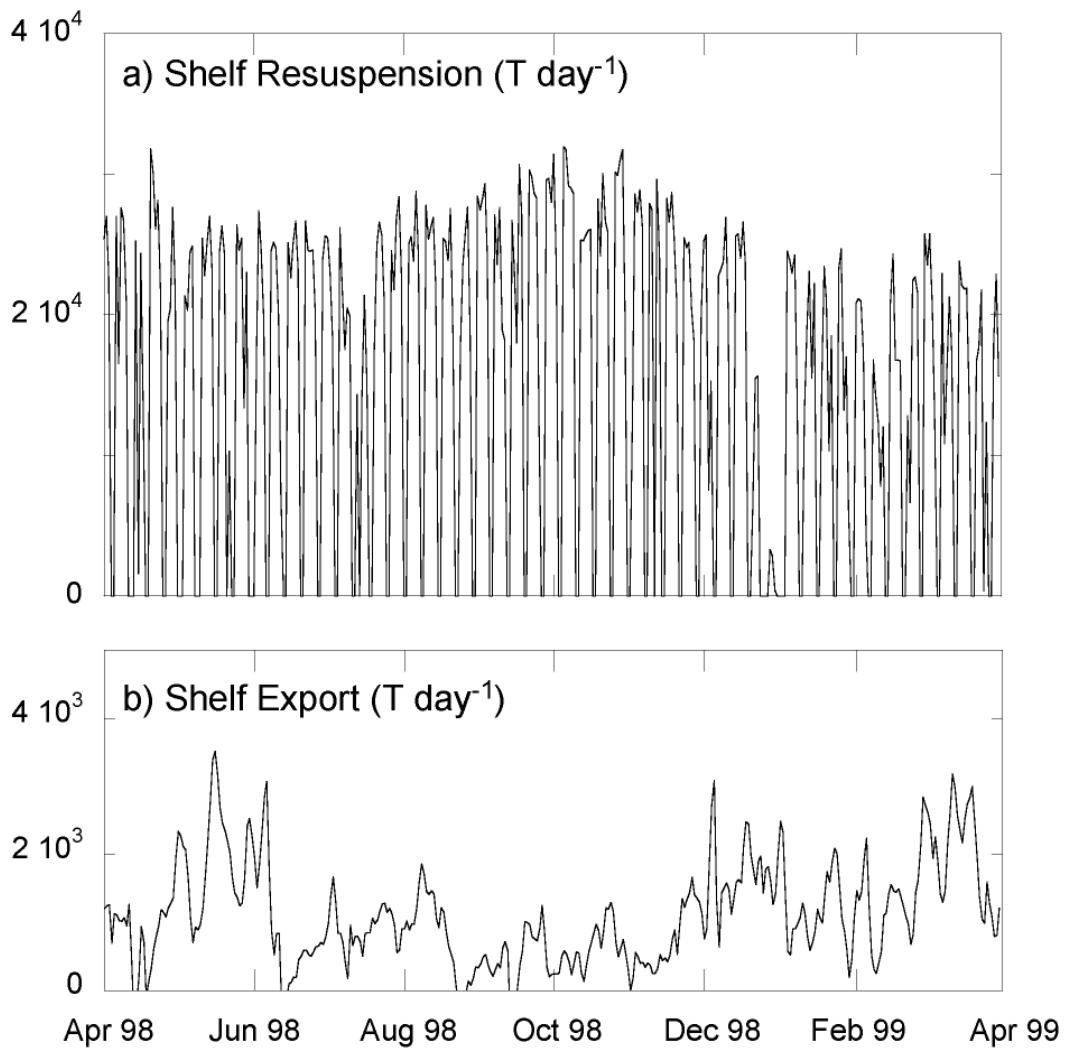


Ferre et al. Figure 7

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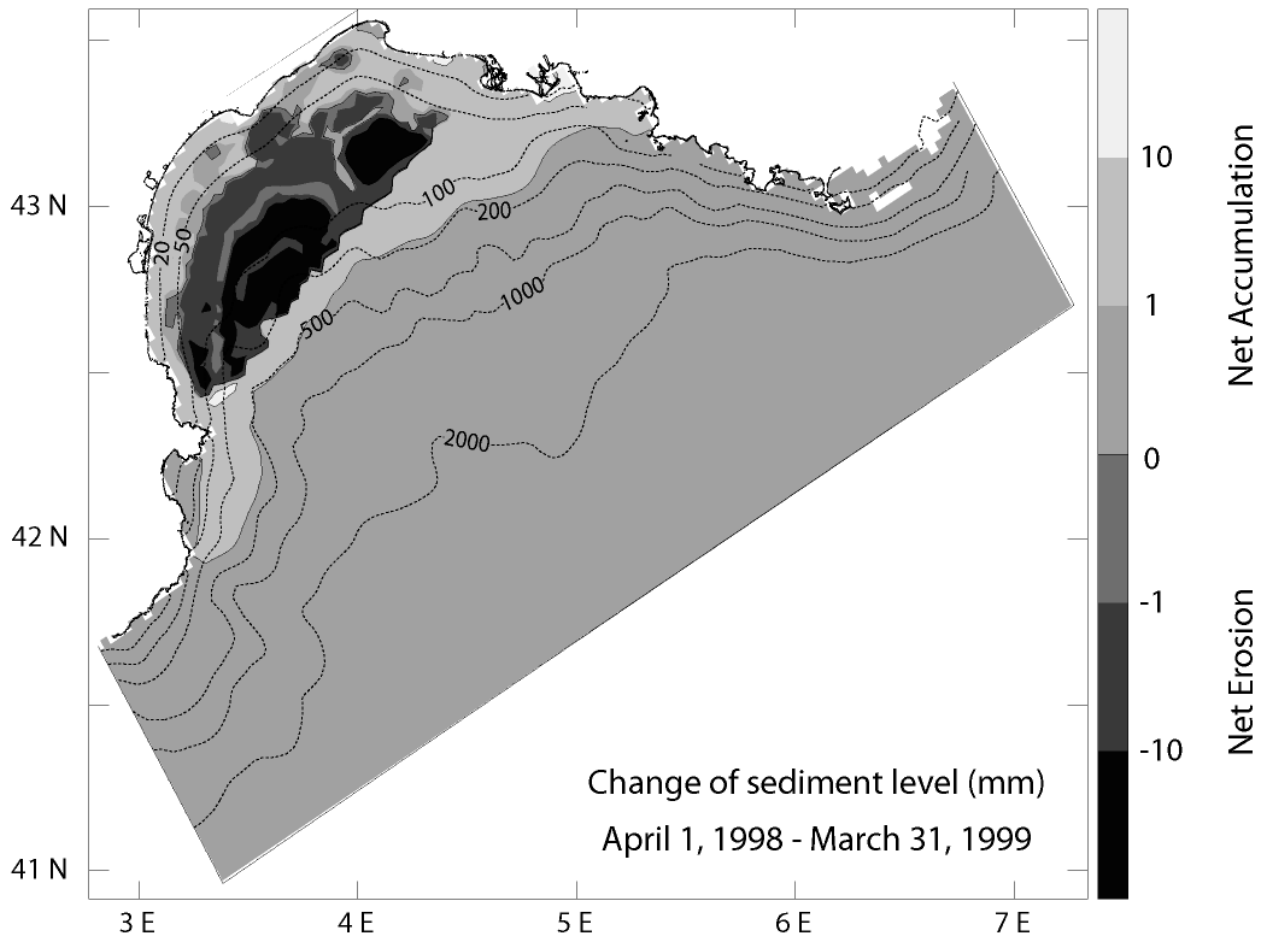


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Ferre et al. Figure 8



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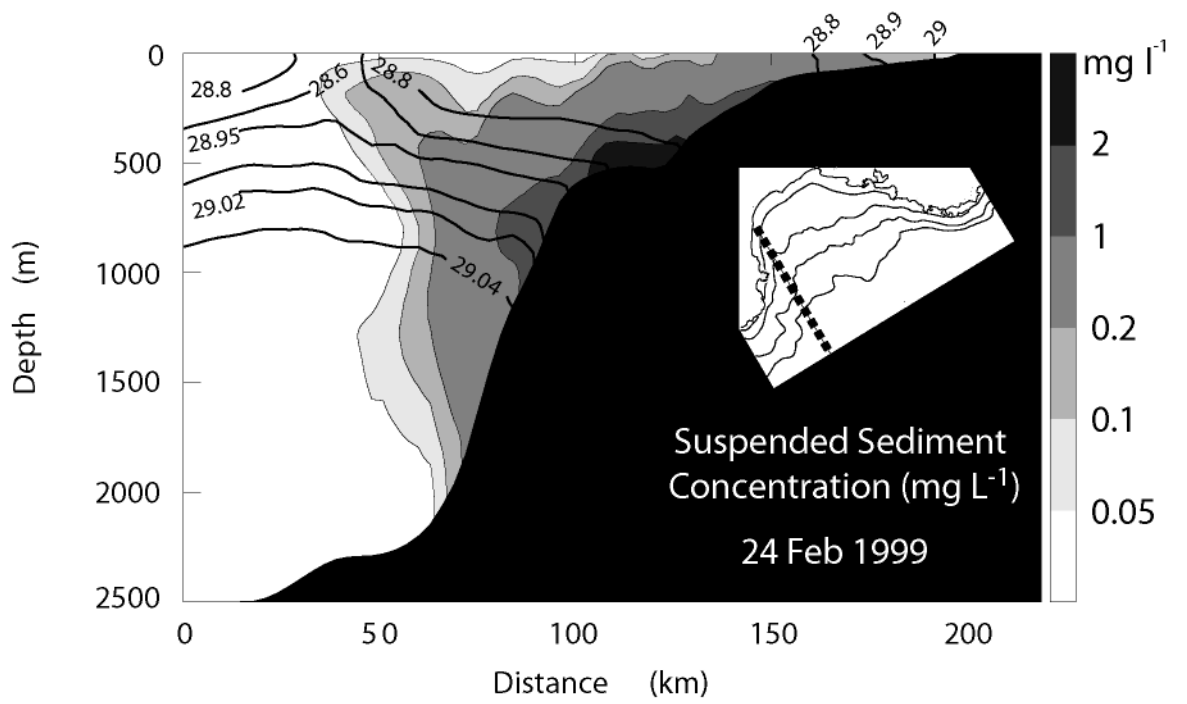
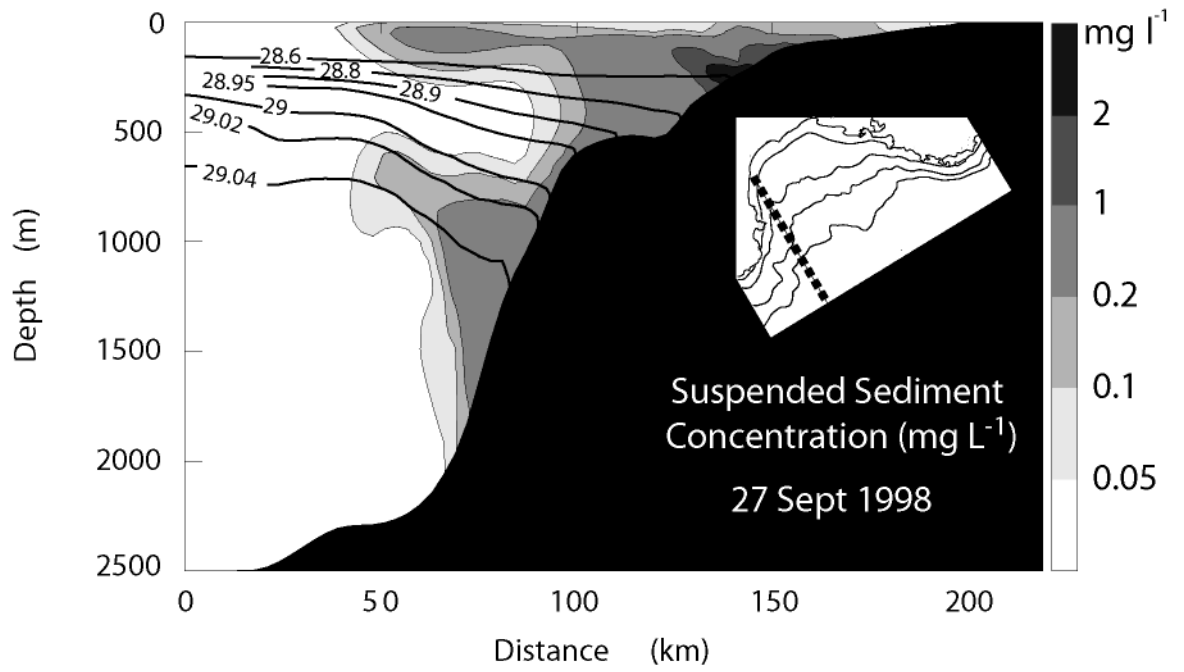
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Ferre et al. Figure 9

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Ferre et al. Figure 10



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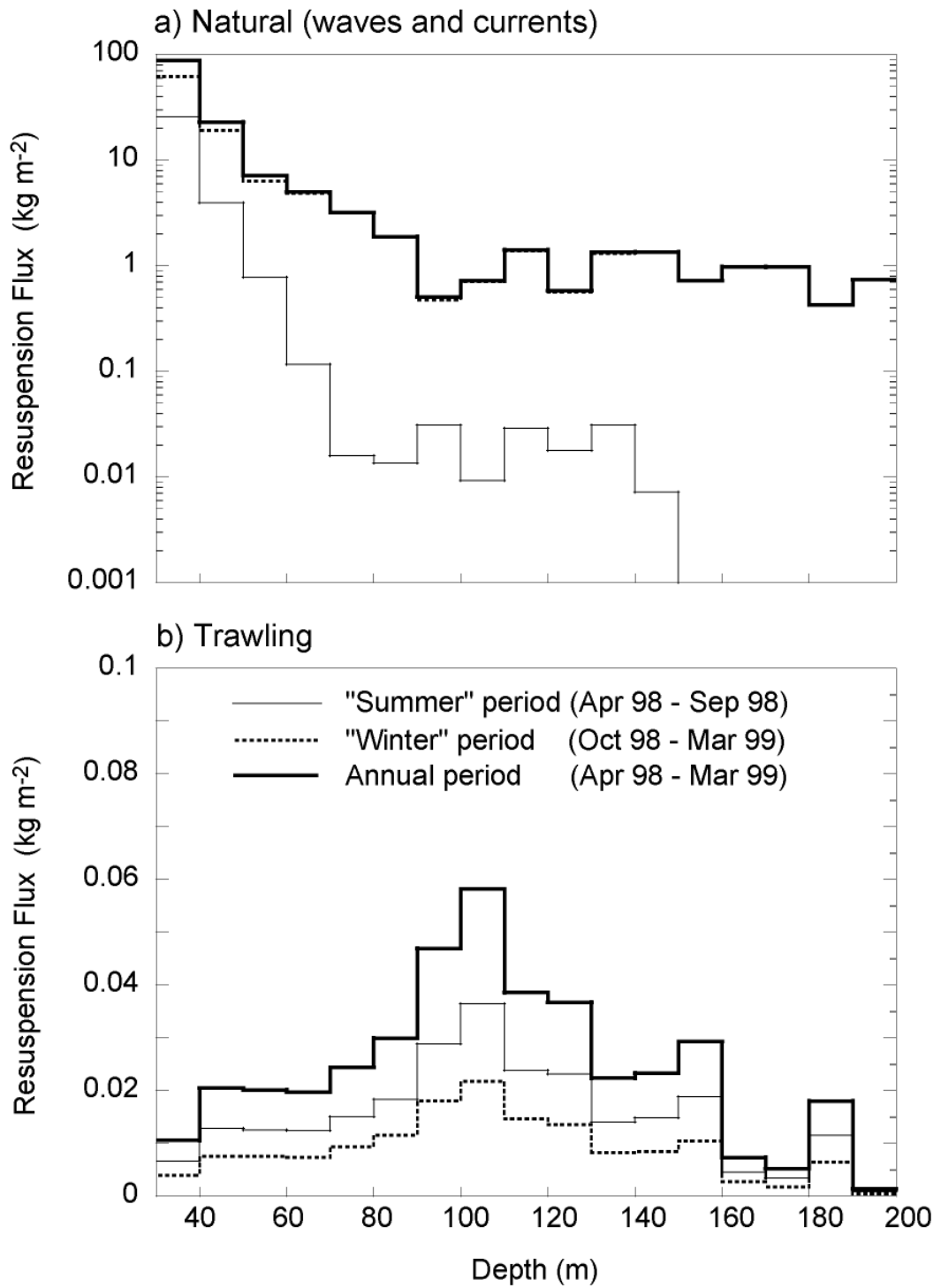
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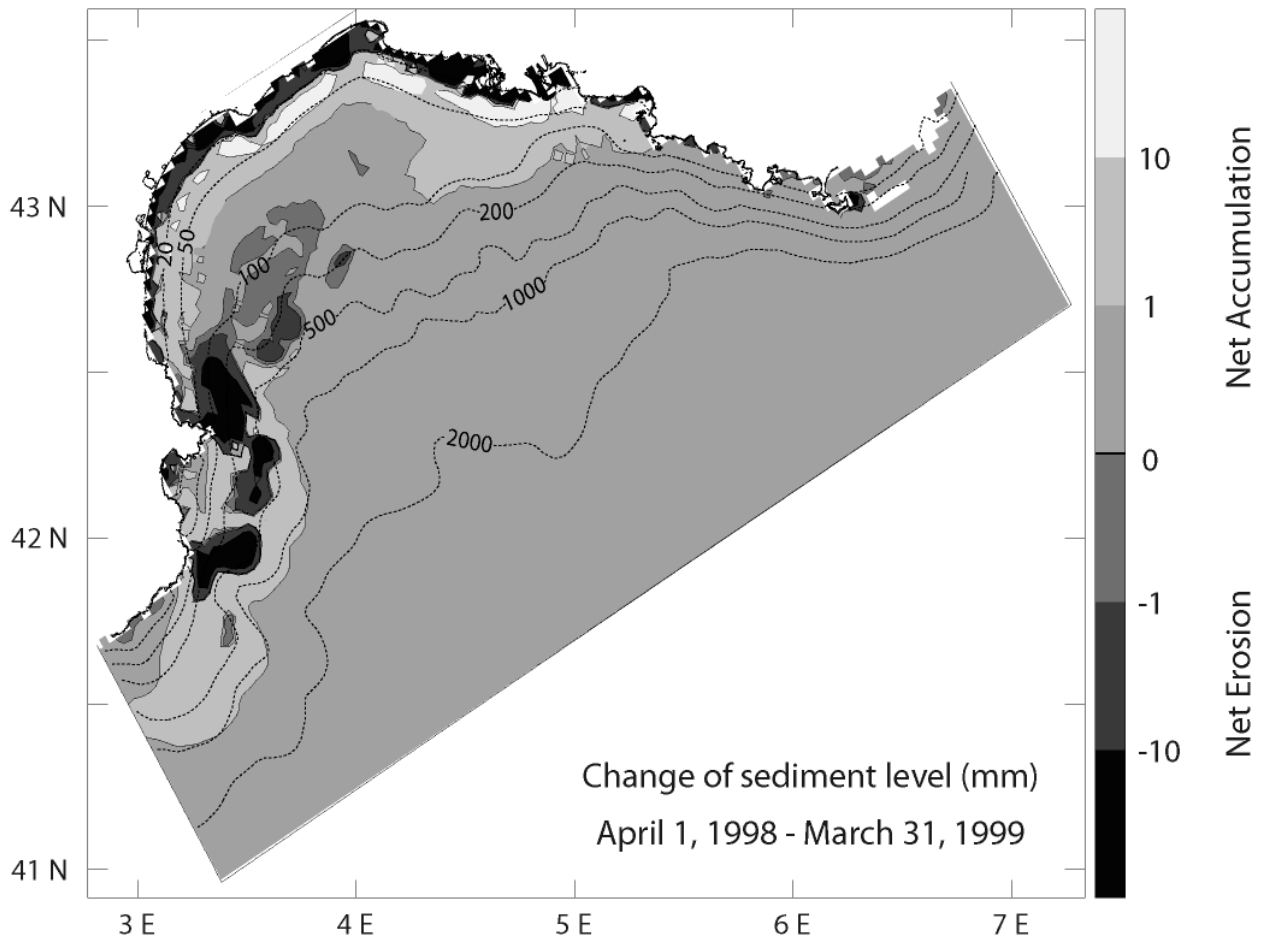


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Ferre et al. Figure 11

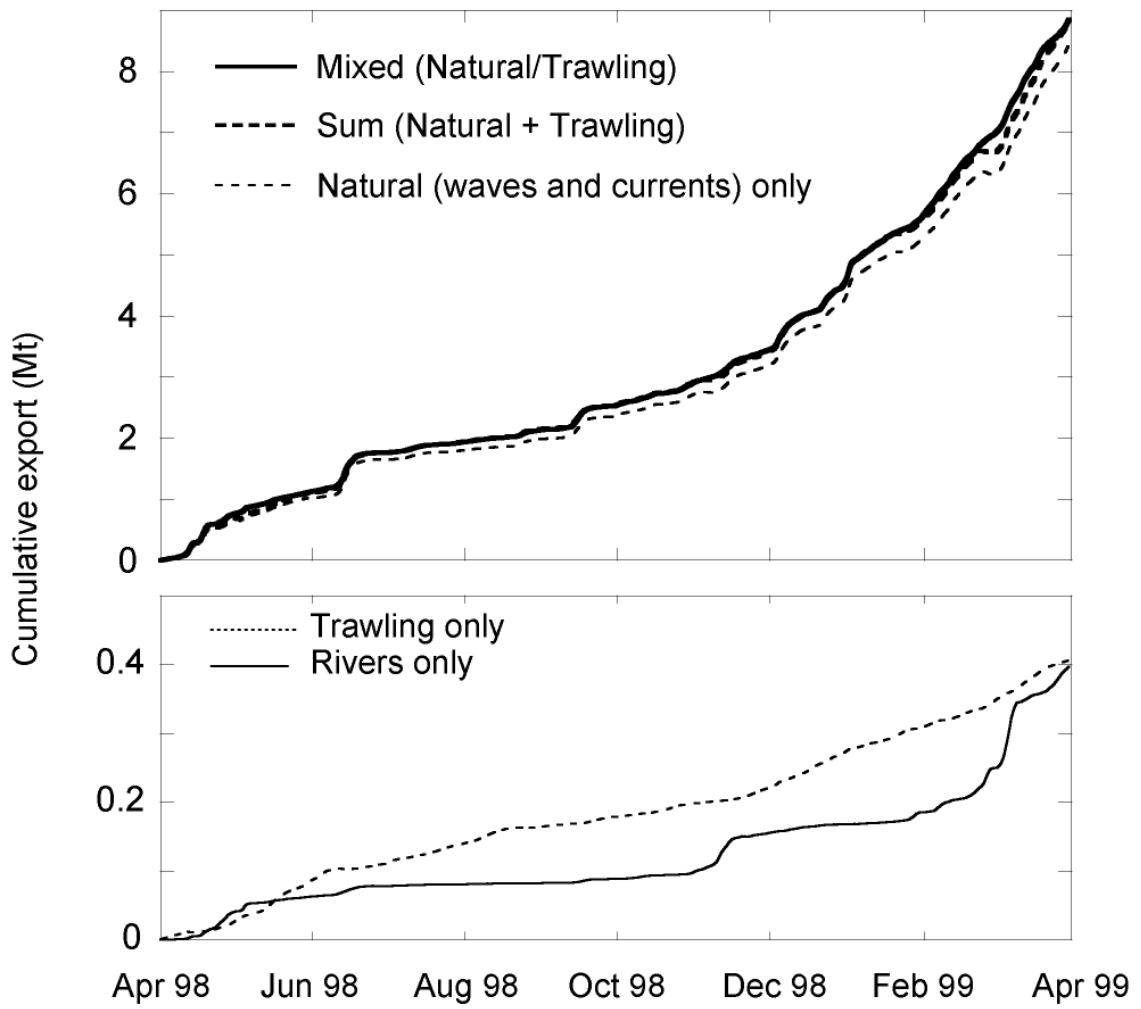
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Ferre et al. Figure 12

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Ferre et al. Figure 13

1067 Table 1. Characteristics of particle grain size classes used in the sediment transport model

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<b>Class</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>	<b>6</b>	<b>7</b>	<b>8</b>	<b>9</b>
category	clay	Fine silt	Coarse silt	Very fine sand	Fine sand	Median sand	Coarse sand	Aggregates	
$D_{50}$ ( $\mu\text{m}$ )	2.43	8.39	31.6	92.4	179.21	317	1063	31.6	129.5
$W_s$ ( $\text{m s}^{-1}$ )	$4.6 \times 10^{-6}$	$5.5 \times 10^{-5}$	$7.7 \times 10^{-4}$	$6.6 \times 10^{-3}$	$2.0 \times 10^{-2}$	$4.1 \times 10^{-2}$	$1.6 \times 10^{-1}$	$1.1 \times 10^{-4}$	$5.9 \times 10^{-4}$
$\rho$ ( $\text{kg m}^{-3}$ )	2650	2650	2650	2650	2650	2650	2650	1264	1097

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1071 Table 2. Annual sediment fluxes integrated between April 01, 1998 and March 31, 1999. Scenarios with Storms and /or Trawling  
 1072 resuspension include sediment input by rivers. Deposition rate for these scenarios excludes the deposited and exported sediment  
 1073 directly deriving from rivers. Once riverine sediment has been deposited on the shelf it is accounted in the resuspension, and  
 1074 subsequent deposition and export fluxes.

<b>Scenario</b> <b>Sed Fluxes</b>	<b>Rivers</b>	<b>Storms</b>	<b>Trawling</b>	<b>Sum</b> <b>(Storms + Trawling)</b>	<b>Mixed</b> <b>(Storms and Trawling)</b>
<i>River Discharge</i> (10 <sup>6</sup> T y <sup>-1</sup> )	3.6	3.6	3.6	3.6	3.6
<i>Shelf Erosion</i> (10 <sup>6</sup> T y <sup>-1</sup> )	0	35264.6	5.6	35270.2	35209.4
<i>Shelf Deposition</i> (10 <sup>6</sup> T y <sup>-1</sup> )	3.1	35255.4	5.2	35260.6	35200.1
<i>Shelf (Erosion- Deposition)</i> (10 <sup>6</sup> T y <sup>-1</sup> )	-3.1	9.2	0.4	9.6	9.3
<i>Shelf export</i> (10 <sup>6</sup> T y <sup>-1</sup> )	0.4	8.5	0.4	8.9	8.9

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