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► **To cite this version:**

Mathieu Chatelain, Katell Guizien. Modelling coupled turbulence – Dissolved oxygen dynamics near the sediment–water interface under wind waves and sea swell. *Water Research*, 2010, 44 (5), pp.1361-1372. 10.1016/j.watres.2009.11.010 . hal-02955078

**HAL Id: hal-02955078**

**<https://hal.science/hal-02955078>**

Submitted on 2 Dec 2022

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# Modelling coupled turbulence - dissolved oxygen dynamics near the sediment-water interface under wind waves and sea swell

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## Abstract

A one-dimensional vertical unsteady numerical model for diffusion-consumption of dissolved oxygen (DO) above and below the sediment-water interface was developed to investigate DO profile dynamics under wind waves and sea swell (high-frequency oscillatory flows with periods ranging from 2 to 30 s). We tested a new approach to modeling DO profiles that coupled an oscillatory turbulent bottom boundary layer model with a Michaelis-Menten based consumption model.

The flow regime controls both the mean value and the fluctuations of the oxygen mass transfer efficiency during a wave cycle, as expressed by the non-dimensional Sherwood number defined with maximum shear velocity ( $Sh$ ). The Sherwood number was found to be non-dependent on sediment biogeochemical activity ( $\mu$ ). In the laminar regime, both cycle-averaged and variance of the Sherwood number are very low ( $\overline{Sh} < 0.05$ ,  $\text{VAR}(Sh) < 0.1\%$ ). In the turbulent regime, the cycle-averaged Sherwood number is larger ( $\overline{Sh} \approx 0.2$ ). The Sherwood number also has intra-wave cycle fluctuations that increase with the period and maximum shear velocity ( $\text{VAR}(Sh)$  up to 30%). Our computations show that DO mass transfer efficiency under high-frequency oscillatory flows in the turbulent regime are water-side controlled by: (a) the diffusion time across the diffusive boundary layer and (b) diffusive boundary layer dynamics during a wave cycle. As a result of these two processes, when the wave period decreases, the  $Sh$  minimum increases and the  $Sh$  maximum decreases. Thus  $\overline{Sh}$  values vary little, ranging from 0.17 to 0.23. For periods up to 30 s, oxygen penetration depth into the sediment did not show any intra-wave fluctuations. Values for the laminar regime are small ( $\leq 1$  mm for  $\mu=2000$  g m<sup>-3</sup> d<sup>-1</sup>) and decrease when the flow period increases. In the turbulent regime, the oxygen penetration depth reaches values up to five times larger than those in the laminar regime, becoming asymptotic as the maximum shear velocity increases.

Keywords: wave boundary layer - mass transfer - turbulent diffusion - unsteady flow - sediment diagenesis

# 1 Introduction

Diffusional mass transfer between bottom sediments and overlying water constitutes an essential coupling for benthic and pelagic ecosystems (Boudreau and Jørgensen, 2001). Transfer of oxygen across the sediment-water interface (SWI) regulates biological and geochemical processes of organic matter degradation in the upper sediment. Vertical oxygen mass transfers at the benthic or bottom boundary layer occur in a zone where gradients in physical, chemical and biological properties are sharp. In the water column, solute transport is dominated by turbulent mixing, except within the diffusive boundary layer (DBL) where turbulence diffusivity becomes negligible compared to oxygen molecular diffusion (Gundersen and Jørgensen, 1990). The thickness of the DBL regulates the kinetics of oxygen supply to the benthic organisms: while a thick DBL associated with small steady flow velocities (laminar regime) may be limiting for organisms with high oxygen uptake rates, a thin DBL associated with large steady flow velocities (turbulent regime) results in the highest possible oxygenation (Nakamura and Stefan, 1994; Hondzo, 1998; Steinberger and Hondzo, 1999). In nature, flows are generally turbulent with DBL thicknesses on the order 1–2 mm (Jørgensen and Revsbech, 1985) but they are also more often unsteady. As a consequence, the DBL thickness will fluctuate inducing oxygen profile dynamics (Jørgensen and Des Marais, 1990; Glud et al., 2007). Yet, such dynamics are not instantaneously responding to the hydrodynamic forcing. Transient oxygen profiles were observed in sediment cores immediately after stirring was stopped (Lohse et al., 1996). Numerical simulations have shown that the duration of the transitory regime between two steady states (with and without flow) decreases as both oxygen consumption and flow velocity increase (Higashino et al., 2004).

Amongst unsteady flows, oscillatory flows are of particular interest for the diffusion-consumption of oxygen at the SWI. Periodic flows are frequent in nature as they are linked to surface gravity waves. In the oceans, such flows are the most energetic (Massel, 1996) and they often destabilize the SWI in the nearshore zone (Harris and Coleman, 1998). Surface gravity wave energy is equally distributed between two types characterized by their period: wind waves and swell (periods from 2 to 30 s) and the diurnal and semi-diurnal tides (periods from 12 to 24 h). In lakes and lagoons, the period range for surface gravity waves is generally restricted to wind waves (period  $< 8$  s) due to fetch limitations. But other types of oscillatory flows like a seiche with even longer periods (depending on the basin lengthscale and stratification) can be observed (Proudman, 1953). In 2003, the oxygen profile dynamics linked to periodic bottom layer turbulence under low-frequency waves (lake internal seiche with period of 18 hours) was observed for the first time (Lorke et al., 2003). Additionally, the effect of periodic flows (periods ranging from minutes to hours) on oxygen diffusion in the water column was investigated by numerical simulations (Higashino et al., 2003).

The present study examines the effect of wind waves and sea swell (periods ranging from 2 to 30 s) on oxygen diffusion and consumption at the SWI. Oscillatory flows exhibiting large velocity fluctuations from zero (at flow reversal) to a maximum value (orbital velocity) are associated with these high-frequency gravity waves (Airy, 1845). Near the bed, an oscillatory bottom boundary layer develops which exhibits strong turbulence dynamics with flow relaminarisation around reversal (Jensen et al., 2006) and consequently, large DBL thickness fluctuations at the flow periodicity. Under oscillatory flows, the oxygen concentration distribution dynamics may result not only from the DBL thickness value, but also from its dynamics as well. Hence, a new one-dimensional vertical, unsteady numerical model for diffusion-consumption of dissolved oxygen (DO) above and below the SWI was driven by the turbulent diffusivity associated with the wave bottom boundary layer modelled by Guizien et al. (2003). Wind waves and sea swell were described by idealized monochromatic waves to assess the respective influence of the wave period and orbital velocity. The new model was used to examine three fundamental questions about the dynamics of DO distribution under high-frequency waves. First, what are the characteristic time scales of the forcing that drive the intra-wave dynamics of DO? Second, how does the DO mass transfer vary with the wave period and the orbital velocity (mean value and fluctuations during a wave cycle)? And third, to what extent do wind waves and sea swell drive sediment oxygenation (DO penetration depth)?

## 2 Material and methods

### 2.1 Model formulation

Dissolved oxygen traverses two diffusive boundary layers from the water column into the sediment. The first layer is in the water immediately above the sediment, and the second is in the sediment immediately below the sediment-water interface (Fig. 1).

[Figure 1]

A one-dimensional vertical (1DV) numerical model of the DO balance in water and sediment is proposed. For the sake of simplicity, we assume a constant porosity of the sediment. Advection due to permeability, bioturbation and bioirrigation in the sediment is neglected. Microbial organic matter degradation occurring in the sediment is taken into account, as well as chemical reactions involving oxygen consumption. Both are modelled by Michaelis-Menten consumption kinetics (House, 2003). Such a mathematical formulation allows a constant consumption when the DO concentration is large (*i.e.* non limiting, zero-order kinetics) and a decreasing consumption when DO concentration approaches zero (first-order kinetics). This formulation is thus consistent with both zero flux and concentration for DO at the lower boundary condition deep in the sediment. Moreover, prescribing a constant consumption near the interface assumes that neither acclimatization nor growth of the respiring community occurs inside a wave cycle. Finally, it is assumed that oxygen consumption can be neglected in the water column. Thus we define:

$$\frac{\partial C^*}{\partial t^*} = \frac{\partial}{\partial z^*} \left( D^* \frac{\partial C^*}{\partial z^*} \right) - \alpha \frac{\mu^* C^*}{K_{O_2}^* + C^*} \quad (1)$$

where the non-dimensional parameters are

$$C^* = \frac{C}{C_0}, t^* = \frac{\nu t}{h^2}, z^* = \frac{z}{h}, D^* = \frac{D}{\nu}, \mu^* = \frac{\mu h^2}{\nu C_0}, K_{O_2}^* = \frac{K_{O_2}}{C_0}. \quad (2)$$

$C$  is the DO concentration,  $t$  is time,  $z$  is the vertical coordinate (positive upward),  $D$  is the vertical diffusivity,  $\mu$  is the maximum oxidation rate,  $K_{O_2}$  is the oxygen half-saturation constant, and  $\alpha$  is a numerical constant ( $\alpha=1$  in sediment and  $\alpha=0$  in water). Reference values are  $\nu$  the kinematic viscosity in water,  $C_0$  the bulk water concentration, and  $h$  a length greater than the sum of DBL thickness in water and DO penetration depth in sediment.

In sediment, oxygen vertical diffusivity  $D$  is equal to the effective diffusivity  $D_s$ , which is molecular diffusion corrected for tortuosity. It can be expressed, through Archie's law, as a function of molecular diffusivity and porosity of the sediments (Ullman and Aller, 1982):

$$D_s = \phi^{m-1} D_w \quad (3)$$

where  $\phi$  is the porosity, and  $m$  denotes an exponent corresponding to different kinds of sediment ( $m=3$ , Manheim and Waterman, 1974). Molecular diffusion  $D_w$  for oxygen is assumed constant, using a Schmidt number  $Sc=\nu/D_w=500$  at 20°C (Denny, 1993).

In water, oxygen vertical diffusivity  $D$  is the sum of molecular ( $D_w$ ) and turbulent ( $D_t$ ) diffusivities. Using the analogy between momentum and mass transfer, the turbulent diffusivity ( $D_t$ ) is assumed to be equal to the eddy viscosity ( $\nu_t$ ) in water. The model formulation thus allows time-variations of turbulent diffusivity to account for unsteady hydrodynamics.

Equation (1) is solved using the implicit finite control volume method of Patankar (1980). The spatial computational domain went from  $-h_s$  in the sediment, to  $h_w$  in the water column ( $h = h_s + h_w$ ). Two exponential grids were defined with  $n_s$  points in sediment and  $n_w$  points in water. Each mesh starts at  $z=0$ , reading:

$$|z_{i+1} - z_i| = dz_i = s r^i \quad (4)$$

taking  $(r,s)$  equals  $(r_s, s_s)$  in sediment and  $(r_w, s_w)$  in water. The SWI is the first sediment point, located at  $z=0$  ( $\alpha=1$ ,  $D = D_s$ ). This grid was adopted because it is well adapted to refining the nearbed description of each domain where gradients are sharp. Meshing independence of the computations was studied and showed insensitivity of the results for a resolution that yields  $r_s=1.054$ ,  $s_s=1 \times 10^{-5}$  ( $n_s=194$ ) and  $r_w=1.054$ ,  $s_w=1 \times 10^{-7}$  ( $n_w=320$ ) for sediment and water, respectively (in Eq. 4).

131 Boundary conditions for DO concentration are imposed at the top and the bottom of the calculation  
 132 domain:

$$133 \quad \begin{cases} C^* = 0 & \text{at } z^* = -h_s/h \\ C^* = 1 & \text{at } z^* = h_w/h \end{cases} \quad (5)$$

134 The first condition expresses that all DO reaching the sediment should be utilized within the oxygen  
 135 penetration depth. The second indicates that at the upper limit of the computational domain the water  
 136 column is fully mixed and the oxygen concentration equals the bulk water concentration. Bulk DO  
 137 concentration was arbitrarily set to  $10 \text{ g m}^{-3}$  (Glud et al., 2003).

138 As we are dealing with periodic hydrodynamic forcing, a finite number of time steps ( $n_t=360$ )  
 139 is required to define an entire period cycle, and periodic boundary conditions are applied stating  
 140  $C^*(z, n_t+1)=C^*(z, 1)$ . The equilibrium solution is the solution when the maximum DO concentration  
 141 difference at the same phase during two consecutive cycles was less than a convergence criterion  $\epsilon$ . We  
 142 used  $\epsilon=10^{-8}$  as the convergence criterion.

## 143 2.2 Sediment characteristics and hydrodynamic forcing

144 This study examines the nearbed dynamics of oxygen mass transfer transport under wave forcing  
 145 over a smooth bottom, as can be observed in shallow estuaries open to the sea. Porous silty sediment  
 146 conditions were used (median diameter  $d_{50}=0.002 \text{ cm}$ ; bottom roughness  $k_n=0.005 \text{ cm}$ ; porosity  $\phi =$   
 147  $0.9$ ). The half-saturation constant for DO is set to a constant value ( $K_{O_2}=0.2 \text{ g m}^{-3}$ , Hao et al., 1983).  
 148 Two biogeochemical activities were tested: high oxidation rate ( $\mu=2000 \text{ g m}^{-3} \text{ d}^{-1}$ ) and low oxidation  
 149 rate ( $\mu=50 \text{ g m}^{-3} \text{ d}^{-1}$ , Higashino et al., 2004). These values correspond to oxygen consumption times  
 150 in the sediment of 422 s and 4.8 h, respectively.

151 A linear wave forcing is considered:

$$152 \quad U(t) = U_w \sin\left(\frac{2\pi t}{T}\right) \quad (6)$$

153 where  $T$  is the leading wave period and  $U_w$  is the nearbed orbital velocity.

154 In order to investigate the effect of oscillating flows typical of wind waves to swell on DO uptake  
 155 dynamics, we considered wave orbital velocities ranging from 20 to 200  $\text{cm s}^{-1}$  and periods ranging from  
 156 2 to 30 s. Virtually, any orbital velocity / period couple can be considered, provided the wave stability  
 157 criterion is fulfilled. We excluded some orbital velocity / period couples which are unrealistic as they  
 158 would correspond to unstable breaking waves. Using a breaking-wave criterion of  $H < 0.8 D$  (where  
 159  $H$  is the wave height and  $D$  is the water depth), the orbital velocity restrictions only applied to waves  
 160 with periods shorter than 4 s.

161 Hydrodynamic forcing for the DO model consisted of time-varying eddy viscosity profiles  $\nu_t(z, t)$  in  
 162 the wave boundary layer during a wave cycle. Together with bottom shear stress time series, these were  
 163 computed using a 1DV bottom boundary layer numerical model dedicated to periodic flow (Guizien  
 164 et al., 2003), given the bottom roughness  $k_n$ . The shear velocity  $u^*$  at the bed is then:

$$165 \quad u^*(t) = \sqrt{\frac{\tau(t)}{\rho}} \quad (7)$$

166 where  $\rho$  denotes the water density.

167 [Figure 2]

168 Fig. 2 shows the time evolution during a wave cycle of the shear velocity  $u^*(t)$  for two contrasted  
 169 wave orbital velocities at the same wave period ( $T=15 \text{ s}$ ) to illustrate the laminar and turbulent regime.  
 170 In both regimes, during each half of a wave cycle, shear velocity varies from nearly zero to a maximum  $u_m^*$   
 171 (not a sine form). As typically seen in oscillatory flows, the shear velocity maximum and minimum are  
 172 ahead of the wave velocity outside the boundary layer, showing that small velocities (near the bottom)  
 173 reverse more easily than larger ones (far from the bottom) when the pressure gradient reverses. This  
 174 phase shift decreases from  $45^\circ$  in the laminar case to about  $10^\circ$  in the fully turbulent regime (Fredsoe  
 175 and Deigaard, 1992). For the same reason, turbulent diffusivity (not shown) exhibits a phase shift with  
 176 the outer flow velocity which varies across the boundary layer. A laminar regime is defined as a wave  
 177 period and an orbital velocity for which the phase shift is  $45^\circ$ . It corresponds in our computations to a  
 178 wave Reynolds number below 320:

$$Re_\delta = \frac{U_w \delta}{\nu} \quad (8)$$

with  $\delta = \sqrt{\nu T / \pi}$  the wave viscous boundary layer height (Vittori and Verzicco, 1998). In the turbulent regime, the shear velocity time evolution jumps during the acceleration phase, marking the onset of turbulence that occurs after the boundary layer relaminarisation around flow reversal (Jensen et al., 2006). In the laminar regime, such a jump is absent (flow remains laminar during the entire wave cycle). The laminar regime ( $Re_\delta \leq 320$ ) is shown in light grey on Fig. 3. For the wave climates that were investigated, maximum shear velocities ranged from less than 1 to 8 cm s<sup>-1</sup>. The sensitivity to the wave period is accentuated when the period is small. The dark grey area indicates breaking wave values on the same figure.

[Figure 3]

Fig. 4 displays computed turbulent diffusivity (*i.e.* eddy viscosity) profiles every 30° along half a wave cycle in the turbulent regime. Temporal changes in  $D_t$  values reflect the temporal variations during a wave cycle of the viscous sublayer thickness  $\delta_\nu(t)$  (the area where  $D_t < \nu = 10^{-2}$  cm<sup>2</sup> s<sup>-1</sup>). Consequently, the oxygen DBL thickness  $\delta_D(t)$  (the area where  $D_t < D_w = 2 \times 10^{-5}$  cm<sup>2</sup> s<sup>-1</sup>) also shows temporal variations during a wave cycle, ranging from around  $5 \times 10^{-3}$  to  $3 \times 10^{-2}$  cm for  $T = 25$  s and  $U_w = 120$  cm s<sup>-1</sup> ( $u_m^* = 5$  cm s<sup>-1</sup>). It should be noted that the exponential mesh creates a coarser resolution in  $\delta_D(t)$  computations for large DBL thicknesses.

[Figure 4]

### 2.3 Model analysis

Computational results consisted of DO vertical profiles at different phases during a wave cycle. For each DO profile, we defined the interfacial concentration  $C_w(t)$ , the penetration depth  $\delta_s(t)$  (with  $C^*(z = \delta_s(t)) = 0.001$ ) and the dissolved oxygen uptake (DOU) at the SWI (Fig. 1). The latter is evaluated from Fick's first law of diffusion (Berner, 1980):

$$DOU(t) = -D_w \frac{\partial C}{\partial z} = -\frac{D_w C_0}{\beta(t)}. \quad (9)$$

Practically, the instantaneous DOU(t) is computed taking the slope  $\beta(t)$  of the DO vertical profile over the three first grid points in water, which height is always much smaller than the DBL thickness. The dimensionless Sherwood number,  $Sh$ , is introduced, following Higashino et al. (2003):

$$Sh(t) = \frac{DOU(t) Sc}{u_m^* (C_w(t) - C_0)} \quad (10)$$

where  $u_m^*$  is the maximum shear velocity. The Sherwood number can be interpreted as a ratio between the effective oxygen transfer rate and turbulent diffusion rate. It thus measures the turbulence efficiency to supply oxygen to the sediment. Following Lorke et al. (2003), we defined a time scale  $t_D(t)$  for the oxygen diffusion across the DBL as:

$$t_D(t) = \frac{\delta_D(t)^2}{D_w}. \quad (11)$$

All these time-varying quantities are described by their mean value (indicated by the overline notation) and their variance ( $\text{VAR}(x) = 100 \times \text{RMS}(x) / \bar{x}$  in %, where RMS is Root Mean Square) during a wave cycle.

To go further, a time scale ( $t_w$ ) describing the temporal dynamics of the DBL thickness is introduced:

$$t_w(t) = \frac{\delta_D(t)}{|\frac{\partial \delta_D}{\partial t}|}. \quad (12)$$

This time scale describing the intra-wave DBL dynamics should be compared to the time scale for the establishment of a local DBL. Similar reasoning was adopted by Lorke et al. (2003), where the authors compared relative importance of vertical diffusion versus horizontal advection. When  $t_w(t)$  is larger than  $t_D(t)$ , the DBL thickness varies less rapidly than the time required for the DBL to establish: diffusive

222 fluxes will follow the local DBL thickness fluctuations. Conversely when  $t_w(t)$  is smaller than  $t_D(t)$ , the  
 223 DBL thickness varies more rapidly than the time required for the DBL to establish: transient diffusive  
 224 fluxes corresponding to average DBL thickness over the period are simulated.

## 225 3 Results

### 226 3.1 Intra-wave cycle dynamics

227 In the laminar regime (shear velocity time series shown on Fig. 2 for  $T=15$  s,  $U_w=10$  cm s<sup>-1</sup>,  
 228  $u_m^*=0.8$  cm s<sup>-1</sup>,  $Re_\delta=218$ ), the time required by oxygen to diffuse through the DBL ( $t_D$ ) during the  
 229 wave cycle was very large ( $\approx 1.1$  days) compared to both the oxygen consumption time in the sediment  
 230 ( $t_c$ ) and the wave period ( $T$ ). The values of  $t_D$  were also fairly constant during the wave cycle (data  
 231 not shown). Consequently, both  $DOU$  and concentration at the SWI displayed very small and constant  
 232 values ( $DOU=0.12$  g m<sup>-2</sup> d<sup>-1</sup>,  $C_w=0.01 C_0$ ). The oxygen penetration depth was also very small  
 233 ( $\delta_s=0.03$  cm). When  $t_D \gg t_c$ , oxygen is consumed more rapidly in the sediment than it diffuses from  
 234 water into the sediment: SWI oxygenation is limited by the transfer time through the water DBL.

235 In the turbulent regime, the time required by oxygen to diffuse through the DBL ( $t_D$ ) is much  
 236 shorter than in the laminar regime, and reaches lower values than oxygen consumption time in the  
 237 sediment ( $t_c$ ). Figure 5 shows the dynamics during a wave cycle of the parameters  $u^*$ ,  $t_D$ ,  $DOU$  and  
 238  $C_w/C_0$  for a 15 s period wave with  $U_w=128$  cm s<sup>-1</sup> ( $u_m^*=5$  cm s<sup>-1</sup>,  $Re_\delta=2797$ ) and the highest oxygen  
 239 consumption rate in the sediment ( $\mu=2000$  g m<sup>-3</sup> d<sup>-1</sup>,  $t_c=432$  s). The oxygen diffusion time through  
 240 the DBL ( $t_D$ ) varied from less than 2 s to about 40 s during each half a wave cycle, with  $\overline{t_D}=10$  s.  
 241 SWI oxygenation is no longer limited by the transfer time through the DBL, resulting in a much higher  
 242  $DOU$  and interfacial concentration ( $\overline{DOU}=2.1$  g m<sup>-2</sup> d<sup>-1</sup>,  $\overline{C_w}=0.86 C_0$ ), and a higher penetration  
 243 depth ( $\overline{\delta_s}=0.12$  cm) compared to the laminar regime.

244 [Figure 5]

245 Values of  $t_D$  exhibited periodic fluctuations every half a wave cycle (Fig. 5b): it had a maximum  
 246 around flow reversal and dropped rapidly at the onset of turbulence during flow acceleration. It decreased  
 247 more gently until shear velocity reached a maximum (turbulent period labelled  $\theta_1$ ). As the shear velocity  
 248 decreased,  $t_D$  increased slightly during the turbulent period labelled  $\theta_2$ . Then it increased more rapidly  
 249 as the bottom boundary layer became laminar during flow deceleration (relaminarization period labelled  
 250  $\theta_3$ ) to reach its maximum value again when the outer flow speed is zero. During  $\theta_1$  and  $\theta_2$ ,  $t_w$  is longer  
 251 than  $t_D$  (bold line on Fig.5b) while during  $\theta_3$ ,  $t_w$  is shorter than  $t_D$ . While the  $t_D$  minimum occurs when  
 252 the shear velocity is at a maximum, the  $t_D$  maximum occurs after the shear velocity minimum, close to  
 253 the flow reversal point. This delay reflects the phase lagging of turbulent diffusivity across the bottom  
 254 boundary layer. As a consequence of the  $t_D$  fluctuations, DO concentrations at the SWI also displayed  
 255 intra-wave dynamics: the  $DOU$  at the SWI varied between a minimum and maximum value during each  
 256 half wave cycle, yielding  $VAR(DOU)=14$  % (Fig. 5c). The minimum value of the  $DOU$  occurs at the  
 257 end of the relaminarization period  $\theta_3$ . The  $DOU$  starts to increase at the laminar-turbulent transition  
 258 when diffusion time had strongly decreased, reaches a maximum during the turbulent period, and  
 259 then decreased until the next laminar-turbulent transition. It is noteworthy that during  $\theta_3$ , the  $DOU$   
 260 decreases steadily without reflecting the large fluctuations of  $t_D$  around flow reversal. As a result of the  
 261  $DOU$  fluctuations, oxygen concentration at the SWI exhibited similar intra-wave fluctuations, although  
 262 those were damped ( $VAR(C_w/C_0)=1$  %, Fig. 5d) and delayed compared to the  $DOU$  fluctuations.  
 263 Finally, the penetration depth did not display any intra-wave dynamics.

### 264 3.2 Effect of the wave period and orbital velocity

265 Fig. 6 shows the temporal evolutions of  $t_D$ ,  $DOU$  and  $C_w/C_0$  during a wave cycle for the same  
 266 wave period ( $T=15$  s) and three orbital velocities ( $U_w=62, 128, 195$  cm s<sup>-1</sup>), which correspond to three  
 267 maximum shear velocities ( $u_m^*=3, 5, 7$  cm s<sup>-1</sup> respectively) and three Reynolds numbers ( $Re_\delta=1355,$   
 268  $2797, 4261$  resp.). When the maximum shear velocity increases, the minimum value for  $t_D$  decreases from  
 269 5.3 to 0.7 s since the minimum DBL thickness is imposed by the maximum shear velocity. Moreover,  
 270 the onset of turbulence occurs at an earlier phase during the accelerating phases of the wave cycle and  
 271 the duration of period  $\theta_1$  increases. The duration of the relaminarization period  $\theta_3$  decreases from 5  
 272 to 2.6 s which limits the laminar DBL development around flow reversal. The maximum values for  
 273  $t_D$  around flow reversal decreases, although remaining larger than the wave period for the three cases

274 shown on Fig. 6a. As far as  $DOU$  is concerned (Fig. 6b), when the maximum shear velocity increases,  
 275 the maximum value of the  $DOU$  increases while the minimum value of the  $DOU$  decreases, being  
 276 phase locked to the laminar-turbulent transition. Besides, the maximum value of the  $DOU$  occurs at  
 277 an earlier phase during the turbulent period. As a result, intra-wave fluctuations of  $DOU$  and oxygen  
 278 concentration at the SWI (Fig. 6c) increase with the maximum shear velocity. Since the maximum  $DOU$   
 279 increased more than the minimum  $DOU$ , cycle-averaged values for  $DOU$  also tend to increase with the  
 280 maximum shear velocity, although the values are close:  $\overline{DOU}$  ranges from 1.99 to 2.16  $\text{g m}^{-2} \text{d}^{-1}$ .  
 281 Cycle-averaged values for the oxygen concentration at the SWI also increase when the shear velocity  
 282 increases ( $\overline{C_w}=0.78, 0.86, 0.91 C_0$  for  $u_m^*=3, 5, 7 \text{ cm s}^{-1}$  respectively). It is interesting to note that  
 283 while the  $C_w$  response to  $DOU$  fluctuations during a wave cycle is attenuated, its response to changes  
 284 of cycle-averaged values of  $DOU$  is amplified.

285 [Figure 6]

286 Fig. 7 shows the temporal evolutions of  $t_D$ ,  $DOU$  and  $C_w/C_0$  during a wave cycle for the same  
 287 maximum shear velocity ( $u_m^*=5 \text{ cm s}^{-1}$ ) and three wave periods ( $T=7, 12, 25 \text{ s}$ ), which correspond to  
 288 three Reynolds numbers ( $Re_\delta=1627, 2404, 3865$  resp.). For the three periods, the oxygen diffusion time  
 289 ( $t_D$ ) reached the same minimum value when the shear velocity is maximum, which occurred around  
 290 the same phase in the three cases: the minimum DBL thickness is imposed by the maximum shear  
 291 velocity which is the same for the three cases depicted on Fig. 7a. However, as the period increases,  
 292 not only the time between two flow reversal increases, but also the laminar-turbulent transition occurs  
 293 at an earlier phase during the accelerating phases of the wave cycle. Consequently, the duration of the  
 294 turbulent periods ( $\theta_1 + \theta_2$ ) is increased in absolute values and also in proportion of the wave period.  
 295 When the period increases, the duration of the relaminarization period  $\theta_3$  also increases from 2.2 to  
 296 5.1 s, which facilitates the relaminarization around flow reversal, yielding larger maximum values for  
 297  $t_D$ . However, in proportion of the wave period, the duration of the period  $\theta_3$  decreases when the wave  
 298 period increases. Regarding the  $DOU$  (Fig. 7b), when the wave period increases, the maximum value  
 299 of the  $DOU$  increases while the minimum value decreases. The fluctuations of  $DOU$  and  $C_w$  during  
 300 the wave cycle (Fig. 7c) thus increase with the period. Although  $DOU$  cycle-averaged values vary little  
 301 with the wave period ( $\overline{DOU}$  ranging from 2.09 to 2.12  $\text{g m}^{-2} \text{d}^{-1}$ ),  $DOU$  exhibits the minimum value  
 302 for  $T=12 \text{ s}$ . Cycle-averaged values for the oxygen concentration at the SWI display the same pattern  
 303 with amplification ( $\overline{C_w}=0.86, 0.85, 0.88 C_0$  for  $T=7, 12$  and  $25 \text{ s}$  respectively).

304 [Figure 7]

### 305 3.3 Trends in cycle-averaged DO quantities

306 A similar dependence for  $\overline{DOU}$ ,  $\text{VAR}(DOU)$ ,  $\overline{C_w}$  and  $\text{VAR}(C_w)$  on the wave characteristics was  
 307 found for high ( $\mu=2000 \text{ g m}^{-3} \text{d}^{-1}$ ) and low ( $\mu=50 \text{ g m}^{-3} \text{d}^{-1}$ ) biogeochemical activities in the sediment.  
 308 The non-dimensional Sherwood number defined by Eq. (10) was used to describe the DO mass transfer  
 309 at the SWI. It also provides a measure of the hydrodynamic efficiency of this mass transfer: the larger  
 310 the Sherwood number, the lower the maximum shear velocity for the higher oxygen transfer at the SWI.  
 311 Since the Sherwood number was non-dependent on the biogeochemical activity of the sediment, it was  
 312 used to summarize the dependency of the DO mass transfer at the SWI on the wave period and the  
 313 orbital velocity (Fig. 8), and finally on the wave Reynolds number (Fig. ??).

314 Laminar flow conditions ( $Re_\delta \leq 320$  on Fig. ?? and light grey areas on Fig. 8) significantly hinder  
 315 the transfer of dissolved oxygen and strongly reduce the presence of oxygen at the SWI, yielding very  
 316 low non-dimensional mass transfer coefficients on average ( $\overline{Sh} < 0.05$ ). Intra-wave cycle fluctuations  
 317 are negligible ( $\text{VAR}(Sh) < 0.1 \%$ , Figs. 8b and ??b). When the wave boundary layer becomes turbulent  
 318 ( $Re_\delta > 320$ ),  $\overline{DOU}$  and  $\overline{C_w}$  displayed larger values than in the laminar regime (up to 2.15  $\text{g m}^{-2} \text{d}^{-1}$   
 319 and 0.9  $C_0$ ). Over the range of wave conditions,  $\overline{Sh}$  varied from 0.17 to 0.23, displaying minimum  
 320 values for wave periods ranging from 10 to 15 s and orbital velocity ranging from 80 to 200  $\text{cm s}^{-1}$   
 321 (Fig. 8a) corresponding to Reynolds numbers between 1500 and 3500 (Fig. ??a). The Sherwood number  
 322 fluctuations during a wave cycle increased with the wave period and orbital velocity (*i.e.* with the  
 323 Reynolds number), yielding  $\text{VAR}(Sh)=30 \%$  (as a result of  $\text{VAR}(DOU)=17 \%$  and  $\text{VAR}(C_w)=1.75 \%$ )  
 324 for  $U_w=200 \text{ cm s}^{-1}$  and  $T=30 \text{ s}$  ( $Re_\delta=6180$ ).

325 [Figure 8]



326 Fig. 9 shows  $\overline{DOU}$  and  $\overline{C_w}/C_0$  versus the cycle-averaged (mean) shear velocity  $\overline{u^*}$  during a wave  
 327 cycle in the laminar and the turbulent regimes, and for two sediment biogeochemical activities. Whatever  
 328 the flow regime,  $\overline{DOU}$  is smaller and  $\overline{C_w}/C_0$  is larger for the less active sediment ( $\mu=50 \text{ g m}^{-3} \text{ d}^{-1}$ )  
 329 than for the more active sediment. In the laminar regime,  $\overline{DOU}$  and  $\overline{C_w}/C_0$  increased linearly with the  
 330 mean shear velocity up to  $1.6 \text{ cm s}^{-1}$ . In the turbulent regime, both quantities reached an asymptote  
 331 for the largest mean shear velocity.

332 [Figure 9]

333 As far as the oxygen penetration depth is concerned, in the laminar regime, it decreased as the wave  
 334 period increased, whatever the orbital velocity and for the two biogeochemical activities (Fig. 10a). The  
 335 oxic layer is thin, ranging from 0.38 to 0.79 cm and from 0.02 to 0.06 cm for  $\mu=50$  and  $\mu=2000 \text{ g m}^{-3} \text{ d}^{-1}$   
 336 respectively. When the overlying flow is turbulent, oxygen penetration depth is thicker and again  
 337 strongly depends on the biogeochemical activity in the sediment ( $\delta_s=1.03$  and  $0.15 \text{ cm}$  for  $\mu=50$  and  
 338  $\mu=2000 \text{ g m}^{-3} \text{ d}^{-1}$  respectively). However, in the turbulent regime, oxygen penetration depth no longer  
 339 depends on the wave period and reaches an asymptote when shear velocity increases (Fig. 10b). For all  
 340 the computations, DO penetration depth never showed intra-wave dynamics (*i.e.*  $\text{VAR}(\delta_s)=0$ ).

341 [Figure 10]

342 Finally, the convergence time ( $t_{st}$ ) of DO profiles from an initial state (where  $C^*=1$  in water and  
 343  $C^*=0$  in sediment) to an equilibrium state was estimated from the calculations (data not shown). In  
 344 the laminar regime,  $t_{st}$  scaled from around 20 to 108 h and from around 20 to 92 h when biogeochemical  
 345 consumption was low ( $\mu=50 \text{ g m}^{-3} \text{ d}^{-1}$ ) and high ( $\mu=2000 \text{ g m}^{-3} \text{ d}^{-1}$ ), respectively). Time to reach  
 346 equilibrium state is shorter when the flow is turbulent (less than 15 h). For the less active sediment,  
 347  $t_{st}$  varied little (between 11 and 13 h) with the wave period or orbital velocity. For the more active  
 348 sediment,  $t_{st}$  ranged from 1 to 15 h, and fastest convergence was obtained for the higher Reynolds  
 349 number.

## 350 4 Discussion

### 351 4.1 Characteristic time scales of non-steady DO dynamics under oscillatory 352 flows

353 Our simulations showed that in the turbulent regime, the periodic fluctuations of the DBL thickness  
 354 under oscillatory forcing induced periodic fluctuations of the DO concentration above and at the SWI.  
 355 These fluctuations are not phase locked, evidence of transient adjustment to DBL thickness fluctuations.  
 356 These features were previously observed on a lake internal seiche with a period of 18 hours (Lorke  
 357 et al., 2003). Below the SWI, fluctuations are rapidly damped out. In the laminar regime, however, no  
 358 fluctuations of the DO concentration were observed, even in the overlying water.

359 Three processes, all with different time scales, interplay during the wave period: (1) the oxygen  
 360 consumption in the sediment, (2) the oxygen diffusion across the DBL, and (3) the DBL periodic  
 361 dynamics. The relative importance of the first two processes was discussed by Higashino et al. (2004)  
 362 for steady flows. In a laminar regime, the oxygen diffusion time across the DBL ( $t_D$ ) is much larger than  
 363 the oxygen consumption time in the sediment ( $t_c$ ): SWI oxygenation is limited by the oxygen supply,  
 364 leading to low values for the  $DOU$  and  $C_w$ . Conversely in a turbulent regime, the oxygen diffusion time  
 365 across the DBL ( $t_D$ ) is strongly reduced and SWI oxygenation is then scaled by the oxygen consumption  
 366 in the sediment ( $t_c$ ). In the case of unsteady wave forcing, the DBL periodicity whose time scale is the  
 367 wave period ( $T$ ) will interfere with the oxygen consumption and diffusion.

368 For high-frequency waves with periods up to 30 s, the sediment oxygen consumption time ( $t_c$ ) will  
 369 always remain longer than the wave period ( $T$ ). Thus, any periodic fluctuation disappears rapidly in  
 370 the sediment. In the turbulent regime, the oxygen diffusion time ( $t_D$ ) can reach shorter values than the  
 371 wave period ( $T$ ): every half a wave period, the  $t_D$  value falls during the turbulent phases  $\theta_1$  and  $\theta_2$ .  
 372 Briefly put, the minimum value of  $t_D$  should be compared to the duration of the turbulent part of the  
 373 wave cycle (Fig. ??).

374 As the wave Reynolds number increases, the minimum value of  $t_D$  decreases and the duration  
 375 of the turbulent phases increases (when  $t_w > t_D$ ).  $DOU$  has then more time to adjust to the lower  
 376 values of the minimum of  $t_D$ , and its intra-wave fluctuations grow. However, when the minimum value  
 377 of  $t_D$  remains longer than the duration of the turbulent part of the wave cycle  $((\theta_1 + \theta_2)/\min(t_D))$ ,

2050 <  $Re_\delta$  < 2500 on Fig. ??), the maximum value of the  $DOU$  will not have time to equilibrate with the low value of  $t_D$ . The maximum values of the Sherwood number are limited by the short duration of the turbulent phases. Consequently, intra-wave fluctuations are supported by the minimum values of the Sherwood number which decrease rapidly. Cycle-averaged value of the Sherwood number ( $\overline{Sh}$ ) decreases. As the wave Reynolds number further increases, the minimum value of  $t_D$  decreases until reaching shorter values than the period  $\theta_1$  ( $\theta_1/\min(t_D)$ ,  $2800 < Re_\delta < 3300$  on Fig. ??). The maximum value of the Sherwood number increases rapidly, following the decrease of the  $t_D$  minimum, while the minimum value of the Sherwood number is limited by the duration of the relaminarization period  $\theta_3$ . Cycle-averaged value of the Sherwood number ( $\overline{Sh}$ ) increases.

As a result of the competition between the oxygen diffusion time and the time granted to this rapid diffusion,  $\overline{Sh}$  exhibits a minimum value for  $Re_\delta$  between 2050 and 3300 (light gray area on Fig. ??a), which corresponds to sea swell conditions ( $10 < T < 15$  s and  $80 < U_w < 200$  cm s<sup>-1</sup>). In other words, some sea swells can be less efficient than wind waves (periods below 8 s) for oxygen mass transfer at the SWI.

## 4.2 Comparison with DO dynamics under steady flows

Previous experimental studies investigated the  $DOU$  dynamics under steady flows and showed an increase of the uptake with the flow shear velocity (Booij et al., 1994; Mackenthun and Stefan, 1998; Steinberger and Hondzo, 1999; Tengberg et al., 2004). These results were obtained for various sediment types (natural and artificial), but no indication of the sediment biogeochemical activities were given. Consequently, direct comparison of our results with previous published experimental work cannot be quantitative. However, qualitatively, our study confirm an increase of the  $DOU$  with the shear velocity. To our knowledge, the only study which can be used for a quantitative comparison is the numerical study by Higashino et al. (2004).  $DOU$  levels are quite similar, but the oxygenation at the interface is much greater in the case of steady flows. For  $\overline{u^*}=1$  cm s<sup>-1</sup> and  $\mu=2000$  g m<sup>-3</sup> d<sup>-1</sup>, oxygen transfer efficiency (*i.e.* Sherwood number) deduced from their calculations reaches  $Sh=0.36$  whereas it reaches  $\overline{Sh}=0.25$  in our study.

High-frequency waves are less efficient than steady current for the oxygen mass transfer at the SWI. Such finding should meanwhile be debiased by the occurrence frequency of each flow condition. Over the range of wave conditions we tested, the laminar regime corresponds to orbital velocities lower than 40 cm s<sup>-1</sup> for the periods below 5 s and orbital velocities lower than 15 cm s<sup>-1</sup> for periods up to 25 s. For the smallest periods corresponding to building wind waves (below 5 s), the wave height is also generally small and the laminar regime should be the most frequent regime in the bottom boundary layer, except in very shallow conditions (less than half a meter of water). This situation is likely to be encountered frequently in small closed basins (small lakes, lagoons, etc.).

As the wave period increases (when the wind fetch is larger), the laminar regime would become rarer: for instance, for a wave period of 8 s over 10 m water depth, the wave bottom boundary layer would be turbulent for a wave height  $H$  larger than 0.3 m, yielding  $\overline{Sh}=0.18$ . For  $H=1.6$  m, orbital velocities reach 60 cm s<sup>-1</sup> ( $\overline{u^*}=2.1$  cm s<sup>-1</sup>,  $\overline{Sh}=0.274$ ), and yields on average a high SWI oxygenation ( $\overline{C_w} \approx 0.8 C_0$ ) due to large flux ( $\overline{DOU} > 2$  g m<sup>-2</sup> d<sup>-1</sup>). Such wave conditions are frequently observed at sea (about 50 % of the time on the French Atlantic coast, Butel et al., 2002). After Higashino et al. (2004), reaching  $C_w \approx 0.8 C_0$  under a steady flow requires a lower oxygen flux  $\overline{DOU}=1.8$  g m<sup>-2</sup> d<sup>-1</sup> associated with a lower shear velocity of 1.35 cm s<sup>-1</sup>. Such steady shear velocity values correspond to a current speed of 30 cm s<sup>-1</sup> at 1 m above a smooth bed. Even the most energetic tidal flow will not have such values more than 50 % of the time (Butel et al., 2002). Thus, it may be estimated that waves will promote a higher sediment oxygenation more frequently than steady currents. Additionally, DO profiles respond to the flow within a few hours. Even short events of wind waves or sea swell may notably stimulate shallow sediment oxygenation and oxygen exchange across the SWI.

## 4.3 Comparison with DO dynamics under low-frequency flows

Higashino et al. (2003) already attempted to describe the unsteady diffusional mass transfer under low-frequency periodic flows (periods ranging from 10 s to 10 h). Their numerical modelling was, however, restricted to the water column and they used a time varying water diffusivity derived from Dade (1993) steady-state parameterization. This may be valid for slowly varying flows, but not for high-frequency waves. Time scales of diffusion across the viscous sublayer are of the same order of magnitude as the wave period for high-frequency flows. As a consequence the turbulent shear stresses display

432 a phase lag across the boundary layer (Dohmen-Janssen, 1999) and the phase at which the laminar-  
 433 turbulent transition occurs during each acceleration of the wave cycle depends on the wave Reynolds  
 434 number  $Re_\delta$  (Jensen et al., 2006). These features are well reproduced by the turbulent boundary layer  
 435 model we used to compute the unsteady diffusive forcing (Guizien et al., 2003).

436 To a small extent, the results presented in this paper tally with previous calculations of the oxygen  
 437 distribution dynamics under low-frequency flows (Higashino et al., 2003), as intra-wave fluctuations  
 438 of the Sherwood number effectively tends to zero when the period becomes shorter. Nonetheless,  
 439 regarding the cycle-averaged value of the Sherwood number, our results are in contradiction to the  
 440 afore-mentioned study. Authors reported a decrease of the cycle-averaged Sherwood number with the  
 441 flow period, while we demonstrated a more complex pattern depending on the flow period and orbital  
 442 velocity as well ( $\overline{Sh}$  is minimum around  $T=10-15$  s and  $U_w=120-180$  cm s<sup>-1</sup>). This difference is simply  
 443 explained by the dependence of the maximum value of the Sherwood number on the wave period which  
 444 was lacking in Higashino et al. (2003) study. Only the intra-wave minimum value of the Sherwood  
 445 number increased as the wave period decreased from 10 h to 10 s. Yet, we showed that the values of  
 446 both the maximum and the minimum of the Sherwood number depend on the wave period (given a  
 447 shear velocity maximum).

448 It should also be pointed out that our Sherwood number values ( $\overline{Sh}$  around 0.2) are less than  
 449 half of the values obtained by Higashino et al. (2003) for similar flow conditions ( $\overline{Sh}=0.5$  for  $T=20$  s,  
 450  $u_m^*=1$  cm s<sup>-1</sup>). The authors extrapolated their results to state that when the wave period tends to  
 451 zero, the Sherwood number should approach a maximum corresponding to the Sherwood number value  
 452 for steady-state conditions at the shear velocity maximum. Using the simulations from a study of the  
 453 DOU dynamics under steady flows (Higashino et al., 2004), the upper limit of the Sherwood number  
 454 under periodic flow (when the maximum shear velocity is  $u^*=1$  cm s<sup>-1</sup>) should be  $Sh=0.36$ . We argue  
 455 that  $\overline{Sh}$  values were overestimated by Higashino et al. (2003) probably because the interfacial oxygen  
 456 concentration was assumed as a constant, while it was not in the present study.

#### 457 4.4 Consequences for biological systems

458 Oxygen near the SWI is essential for both biological production and decomposition processes.  
 459 Oxygen concentration is a regulating mechanism for benthic community complexity (Llansó, 1992), for  
 460 regeneration of nutrients (Rahm and Svensson, 1989), and it also constrains chemical (Cai and Sayles,  
 461 1996) and biological (House, 2003) reactions. In a laminar regime, the transfer of DO is strongly impeded  
 462 by the thickness of the DBL and hypoxic conditions ( $C < 2$  ml l<sup>-1</sup>  $\approx 2.4$  g m<sup>-3</sup>, Diaz and Rosenberg,  
 463 1995) may appear near the SWI. A continuous reduction of around 80-90 % in oxygen concentration at  
 464 the SWI ( $C_w=0.1-0.2$   $C_0=1-2$  g m<sup>-3</sup>) may significantly disturb the growth and metabolism of benthic  
 465 organisms and can cause mass mortality of marine animals, resulting in benthic defaunation and fish  
 466 community decline (Diaz and Rosenberg, 1995, and references herein). On the other hand, a turbulent  
 467 regime promotes high levels of SWI oxygenation.

468 Oxygen concentration at the SWI can be dynamically driven by periodic fluctuations of the DBL  
 469 thickness under wind waves and sea swell. Yet the amplitude of these fluctuations during a wave cycle  
 470 may not be sufficient to stress the benthic macrofauna (around 1 % for  $C_w/C_0$  for instance). In the  
 471 sediment, periodic fluctuations vanish rapidly and oxygen penetration depth largely depends on the  
 472 oxygen consumption in the sediment and to a lesser extent, on the wave period in the laminar regime  
 473 (Fig. 10a) and on the shear velocity in the turbulent regime (Fig. 10b). This sediment inertia is explained  
 474 by the larger oxygen consumption time ( $t_c$ ) in the sediment compared to the DBL dynamics time scale  
 475 during a wave period ( $t_w$ ). For flows having periods of hours (tides, inertial waves, etc.) or smaller  
 476 consumption time (*i.e.* smaller  $C_0$ , for instance), it can be expected that  $t_w$  will reach values comparable  
 477 to or even larger than  $t_c$ . In such cases, periodic fluctuations of oxygen concentration may be expected  
 478 not only in the overlying water but also in the sediment. However, the fluctuation range as well as the  
 479 cycle-averaged value are not trivial to extrapolate since a strong coupling between the DBL dynamics,  
 480 the oxygen diffusion across the DBL, and the oxygen consumption in the sediment is likely to exist when  
 481 characteristic time scales ( $t_D$ ,  $t_c$  and  $t_w$ ) have similar orders of magnitude.

482 Finally, sediment oxygen consumption was modelled using a Michaelis-Menten kinetic formulation.  
 483 This formulation assumes explicitly that no acclimatization of the respiring community occurs during a  
 484 wave cycle. Such absence of respiration acclimatization should be tested experimentally as a function of  
 485 the wave period, for instance with high resolution DO measurements. Although promising results have  
 486 accompanied the development of optical methods for oxygen concentration profiling (Revsbech et al.,  
 487 1998), faster oxygen profiles measurements are still required to resolve the temporal dynamics of DO

488 under wind waves and sea swell. Even the novel non-invasive eddy correlation technique (Berg et al.,  
489 2003) requires an integration time of around 150 s, which is still too long to observe high-frequency  
490 fluctuations related to high-frequency wave turbulence. Turbulence and diffusion measurements should  
491 indeed be measured simultaneously with DO profiles at high-frequency to evaluate the tested model  
492 design and the biological interpretations of the mass transfer dynamics at the SWI under periodic  
493 waves.

## 494 5 Conclusions

495 The response of dissolved oxygen profiles to a wide range of wind waves to sea swell conditions  
496 over a smooth bottom was studied. Oxygen diffusion time across the diffusive boundary layer ( $t_D$ ),  
497 dissolved oxygen uptake ( $DOU$ ), interfacial concentration ( $C_w$ ), and oxygen penetration depth ( $\delta_s$ )  
498 were described by their cycle-averaged value and their standard deviation during a wave cycle.

- 499 • As in steady flows, the flow regime (turbulent or laminar) controls both the  $DOU$  and the oxygen  
500 concentration at the SWI. In the laminar regime, oxygen mass transfer efficiency is strongly  
501 impeded, yielding small and constant  $DOU$ ,  $C_w$  and  $\delta_s$  values during the wave cycle. In the  
502 turbulent regime (frequent under waves), oxygen supply to the sediment is no longer limited  
503 resulting in higher values for  $\overline{DOU}$ ,  $\overline{C_w/C_0}$  and  $\delta_s$  (Fig. 8, Fig. 10a and b).
- 504 • In the turbulent regime,  $DOU$  and  $C_w$  exhibit periodic fluctuations in response to the unsteady  
505 DBL thickness: their dynamics were water controlled by the ratio between (a) the diffusion time  
506 across the DBL ( $t_D$ ), and (b) the time allowed for this diffusion during a wave cycle ( $t_w$ ). When  
507  $t_w(t)$  was smaller than  $t_D(t)$ , the DBL thickness varied more rapidly than the time required  
508 for diffusive flux to establish: diffusive flux corresponded to the average DBL thickness over  
509 a period. Conversely, when  $t_w(t)$  was larger than  $t_D(t)$ , diffusive flux followed the local DBL  
510 thickness fluctuations (Fig. 5). Unsteady properties of the overlying high-frequency flow were  
511 never transmitted deeply into the sediment ( $\text{VAR}(\delta_s)=0$ ).
- 512 • Dependence of the oxygen mass transfer efficiency on the wave period and the orbital velocity are  
513 summarized by the non-dimensional Sherwood number ( $Sh$ ) trends. The latter was found non-  
514 dependent on the sediment biogeochemical activity. The cycle-averaged Sherwood values ( $\overline{Sh}$ )  
515 vary little, ranging from 0.17 to 0.23 and with minimum values for sea swells having periods  
516 ranging from 10 to 15 s (Fig. 8a). Intra-wave fluctuations  $\text{VAR}(Sh)$  increase as both wave period  
517 and orbital velocity (*i.e.* Reynolds number) increase, ranging from 0.1 % in the laminar regime  
518 to 30 % in the turbulent regime (Figs. 8b and ??b). Finally, although  $\overline{Sh}$  values remained lower  
519 than values for a steady current with the same maximum shear velocity, high-frequency waves are  
520 likely to promote high sediment oxygenation more frequently than steady currents.

## 521 Acknowledgements

522 We would like to thank Jennifer Guarini for correcting the English and for commenting on an  
523 earlier version of this paper. The critical remarks of two anonymous reviewers helped to improve the  
524 manuscript. This work is a partial fulfillment of the PhD Thesis of Mathieu Chatelain who was supported  
525 by a doctoral fellowship from the French National Center for Scientific Research (CNRS).

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## A Symbols

Symbol	Unit	Description
$C$	$[M].[L]^{-3}$	Dissolved oxygen concentration
$C_0$	$[M].[L]^{-3}$	Bulk water concentration
$C_w$	$[M].[L]^{-3}$	Interfacial concentration
$D$	$[L]^2.[T]^{-1}$	Vertical diffusivity
$DOU$	$[M].[L]^2.[T]^{-1}$	Dissolved oxygen uptake
$D_s$	$[L]^2.[T]^{-1}$	Effective diffusivity
$D_t$	$[L]^2.[T]^{-1}$	Turbulent diffusivity
$D_w$	$[L]^2.[T]^{-1}$	Molecular diffusivity
$d_{50}$	[L]	Median diameter of the sediment grain
$h$	[L]	Length of the computational grid ( $=h_w+h_s$ )
$h_w$	[L]	Modelled water height
$h_s$	[L]	Modelled sediment depth
$k_n$	[L]	Bottom roughness
$K_{O_2}$	$[M].[L]^{-3}$	Dissolved oxygen half-saturation constant
$m$	-	Numerical constant
$n_s$	-	Number of computational points in sediment
$n_w$	-	Number of computational points in water
$n_t$	-	Number of time steps that defines a period
$Re_\delta$	-	Reynolds number
$Sc$	-	Schmidt number
$Sh$	-	Sherwood number
$r, s$	-	Constants for grid definition
$t$	[T]	Time
$t_c$	[T]	Consumption time in sediment
$t_D$	[T]	Diffusion time across diffusive boundary layer
$t_{st}$	[T]	Convergence time of the computations
$T$	[T]	Wave period
$u^*$	$[L].[T]^{-1}$	Bottom shear velocity
$u_m^*$	$[L].[T]^{-1}$	Maximum shear velocity
$U$	$[L].[T]^{-1}$	Wave velocity
$U_w$	$[L].[T]^{-1}$	Nearbed orbital velocity of the flow
$z$	[L]	Y-coordinate (positive upward)
$\alpha$	-	Numerical constant
$\beta$	$[L]^4$	Slope of oxygen profile at sediment-water interface
$\delta$	[L]	Wave viscous boundary layer height (Stokes length)
$\delta_D$	[L]	Diffusive boundary layer thickness
$\delta_\nu$	[L]	Viscous sublayer thickness
$\delta_s$	[L]	Oxygen penetration depth
$\epsilon$	-	Convergence criterion
$\mu$	$[M].[L]^{-3}.[T]^{-1}$	Biogeochemical activity of the sediment
$\nu$	$[L]^2.[T]^{-1}$	Kinematic viscosity in water
$\nu_t$	$[L]^2.[T]^{-1}$	Eddy viscosity of the fluid
$\phi$	-	Sediment porosity
$\varphi$	[°C]	Wave phase
$\rho$	$[M].[L]^{-3}$	Water density
$\tau$	$[M].[L]^{-1}.[T]^{-2}$	Bottom shear stress



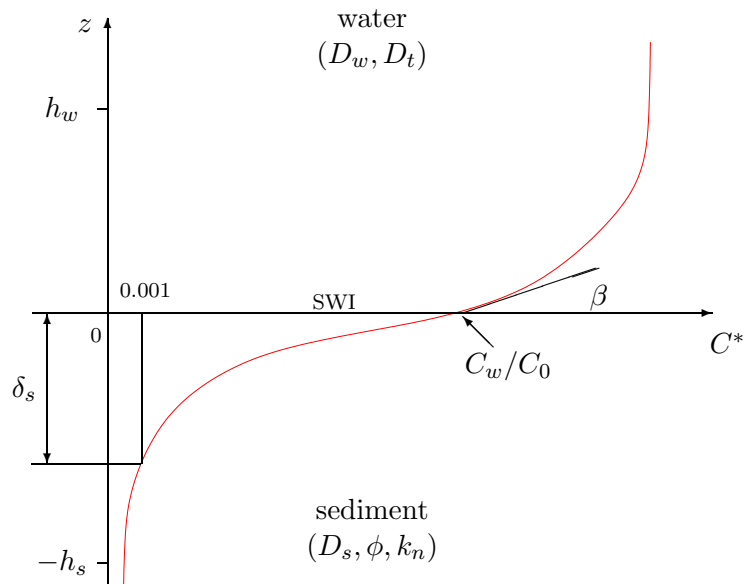


Figure 1: Schematic representation of non-dimensional dissolved oxygen concentration profile ( $C^*=C/C_0$ ) at the sediment-water interface (SWI).

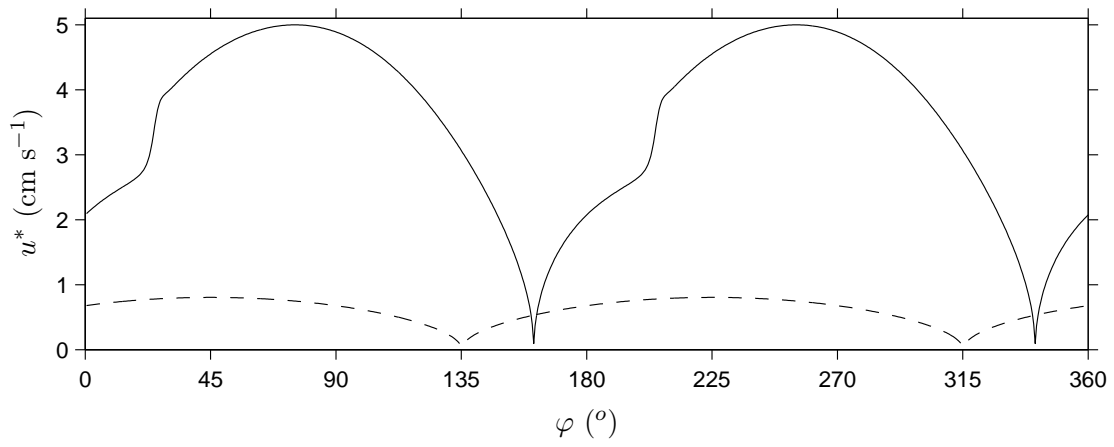


Figure 2: Shear velocity  $u^*$  during a wave cycle for  $T=15$  s, and  $u_m^*=5 \text{ cm s}^{-1}$  (solid line),  $u_m^*=0.8 \text{ cm s}^{-1}$  (dashed line).

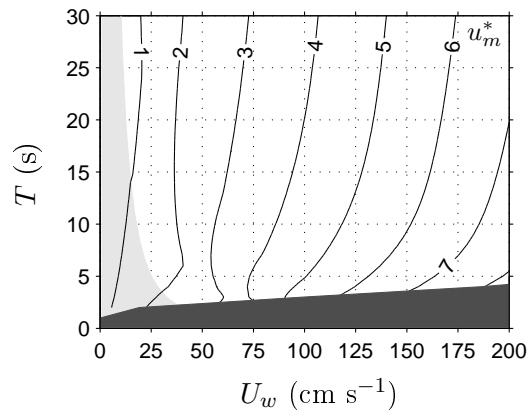


Figure 3: Maximum shear velocity  $u_m^*$  dependence on orbital velocity  $U_w$  and period  $T$  of the wave. Dark grey delimits the unstable breaking waves ( $H < 0.8 D$ ) and light grey delimits the laminar regime ( $Re_s < 320$ ).

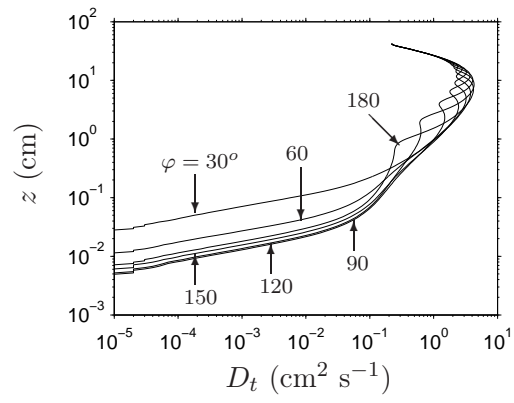


Figure 4: Vertical profiles of turbulent diffusivity  $D_t$  at different wave phases  $\varphi$ , for  $u_m^* = 5 \text{ cm s}^{-1}$  and  $T = 25 \text{ s}$ .

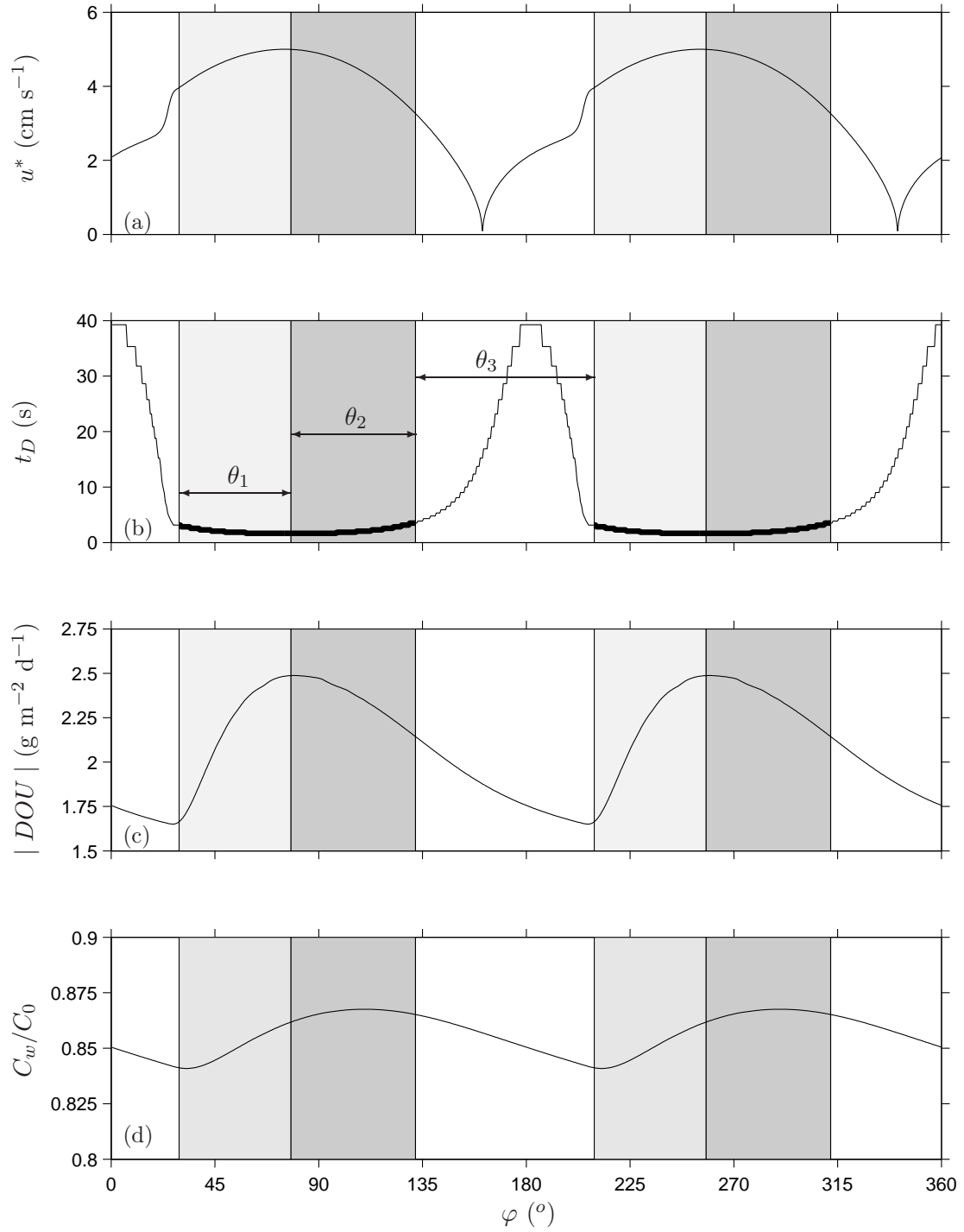


Figure 5: Temporal evolution of (a)  $u^*$ , (b)  $t_D$ , (c)  $DOU$ , and (d)  $C_w/C_0$  during a wave cycle, for  $u_m^*=5$  cm s<sup>-1</sup>,  $T=15$  s, and  $\mu=2000$  g m<sup>-3</sup> d<sup>-1</sup>. Light grey delimits the turbulent period  $\theta_1$  and dark grey delimits the turbulent period  $\theta_2$ .

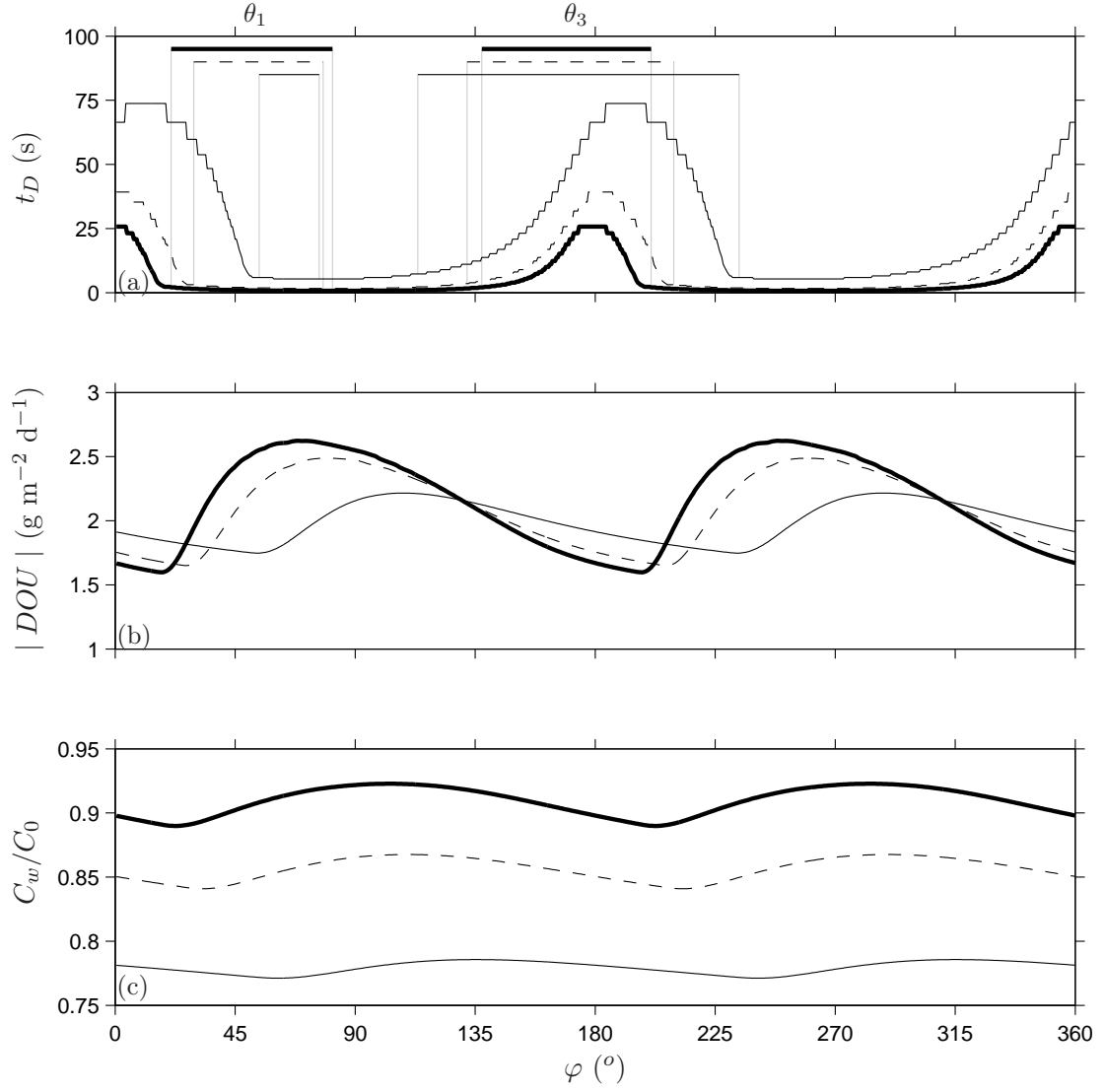


Figure 6: Temporal evolution of (a)  $t_D$ , (b)  $DOU$ , and (c)  $C_w/C_0$  during a wave cycle, for  $T=15$  s,  $\mu=2000 \text{ g m}^{-3} \text{ d}^{-1}$ , and  $u_m^*=3 \text{ cm s}^{-1}$  (solid line),  $u_m^*=5 \text{ cm s}^{-1}$  (dashed line),  $u_m^*=7 \text{ cm s}^{-1}$  (bold line).

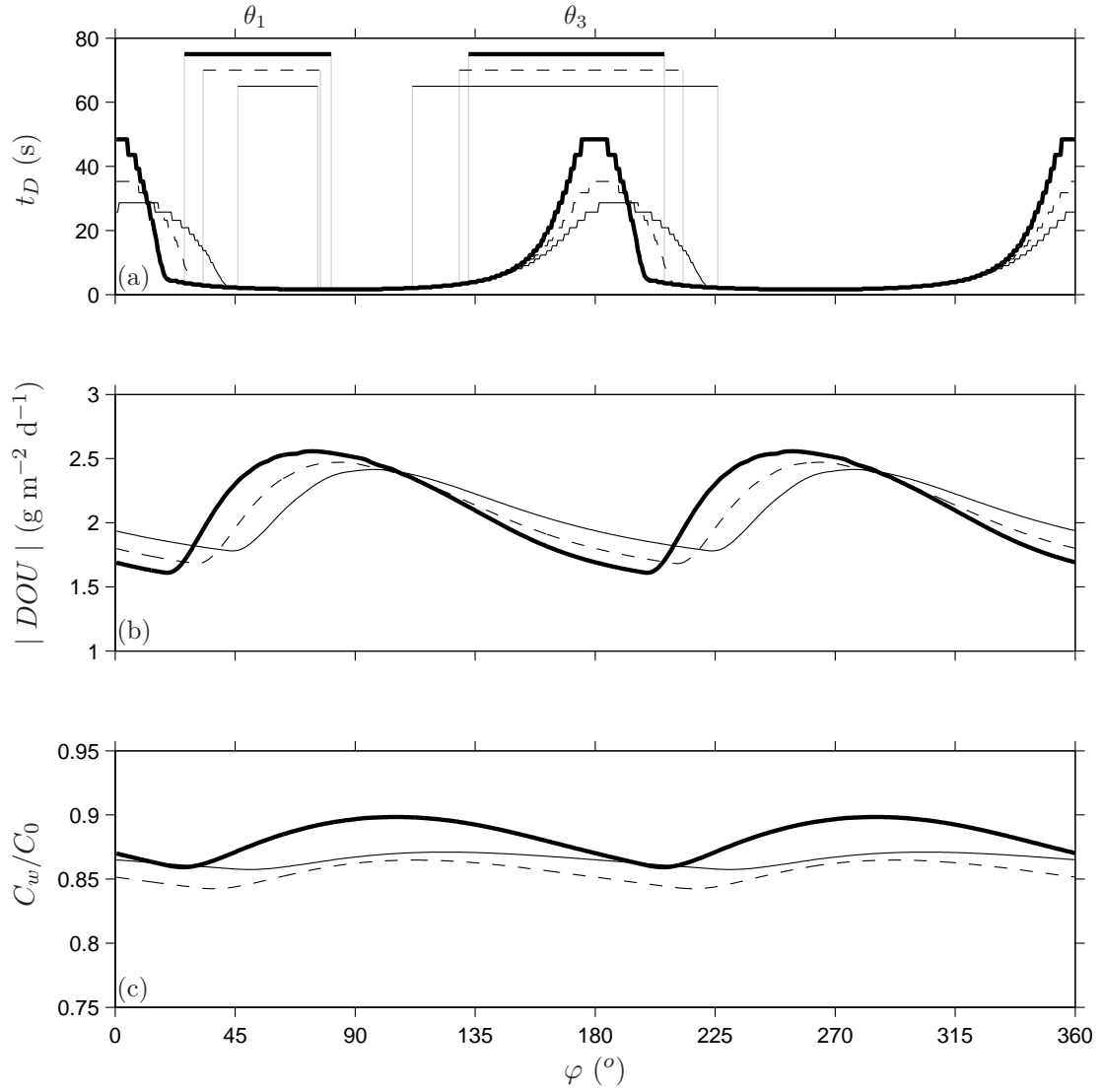


Figure 7: Temporal evolution of (a)  $t_D$ , (b)  $DOU$ , and (c)  $C_w/C_0$  during a wave cycle, for  $u_m^*=5 \text{ cm s}^{-1}$ ,  $\mu=2000 \text{ g m}^{-3} \text{ d}^{-1}$ , and  $T=7 \text{ s}$  (solid line),  $T=12 \text{ s}$  (dashed line),  $T=25 \text{ s}$  (bold line).

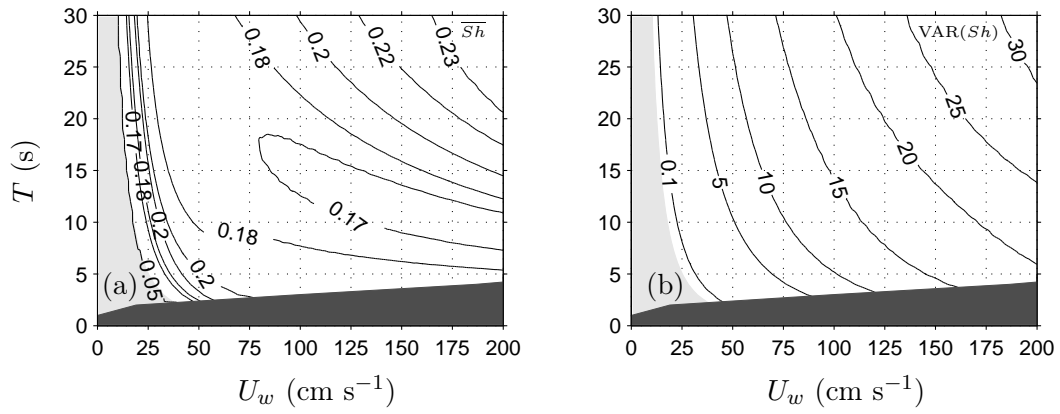


Figure 8: Isograms of (a)  $\overline{Sh}$ , and (b)  $\text{VAR}(Sh)$  showing dependences on orbital velocity  $U_w$  and wave period  $T$ . Dark grey delimits the unstable breaking waves ( $H < 0.8 D$ ) and light grey delimits the laminar regime ( $Re_\delta < 320$ ).



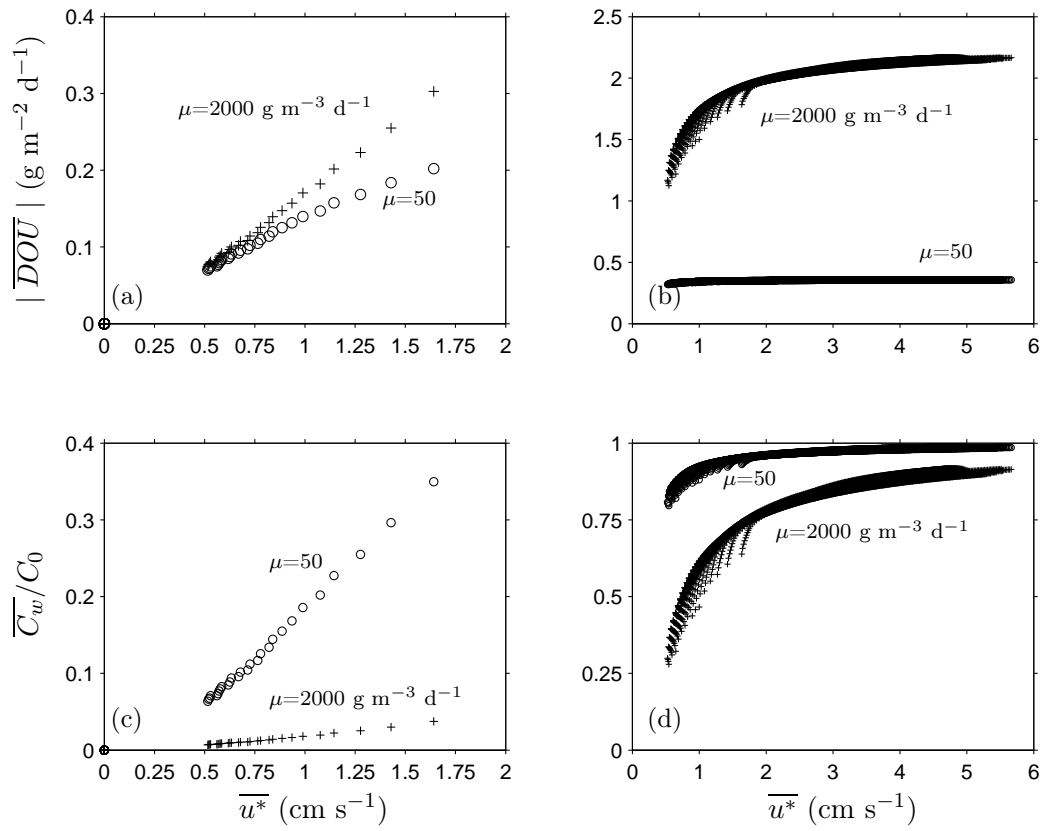


Figure 9: Dependences of  $\overline{DOU}$  (a,b) and  $\overline{C_w}/C_0$  (c,d) on cycle-averaged shear velocity  $\overline{u^*}$  for two biogeochemical activities. (a,c) are for the laminar regime ( $Re_\delta < 320$ ), (b,d) are for the turbulent regime ( $Re_\delta > 320$ ).

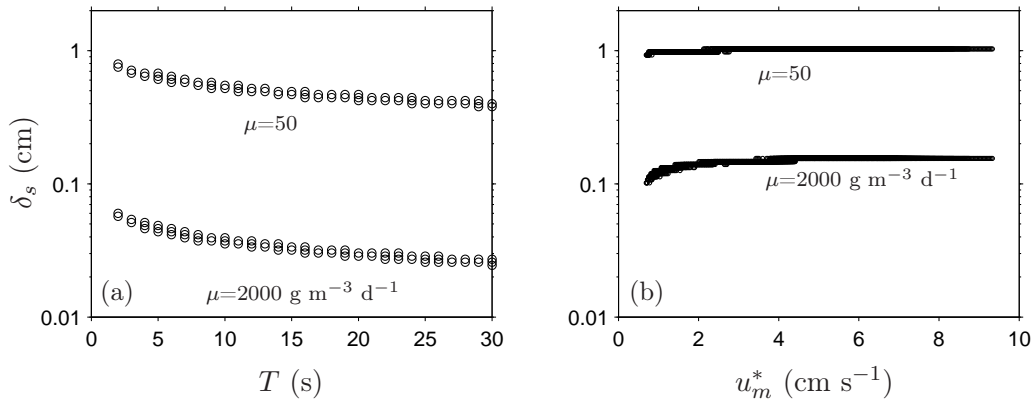


Figure 10: Penetration depth  $\delta_s$  dependence on (a) wave period  $T$  for the laminar regime ( $Re_\delta \leq 320$ ) and (b) maximum shear velocity  $u_m^*$  for the turbulent regime ( $Re_\delta > 320$ ), and the two biogeochemical activities tested.