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1 **Copepods use chemical trails to find sinking marine snow aggregates**

2

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11 Running head: Copepods and marine snow chemical trails

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18 Abstract

19 Copepods are major consumers of sinking marine particles and hence reduce the efficiency  
20 of the biological carbon pump. Their high abundance on marine snow suggests that they can  
21 detect sinking particles remotely. By means of laboratory observations we show that the  
22 copepod *Temora longicornis* can detect chemical trails originating from sinking marine snow  
23 particles (appendicularian houses). The chemical cue was detected by copepods from a  
24 distance of  $> 25$  particle radii, with the probability of detection decreasing with distance. The  
25 behavior of *T. longicornis* following the trail resembled the behavior of males tracking  
26 pheromone trails, although with a lower tracking velocity. Upon finding a house, the copepod  
27 would attach for a short period (10-30 s) and feed intensively. Due to short residence times,  
28 daily feeding rates were moderate. Our results demonstrate that even *T. longicornis*, a species  
29 usually considered a micro-particle feeder, is able to detect and feed on marine snow  
30 aggregates. If similar behaviors are displayed by the more dedicated aggregate-feeding  
31 copepods, a topic that remains unexplored, the effect of copepods on vertical flux attenuation  
32 may be significant.

33       **INTRODUCTION**

34

35       Sinking particles are the main vehicles for the vertical transport of biogenic carbon from  
36 the sea surface to the ocean interior and the seafloor (Fowler and Knauer 1986). The  
37 downward flux of particles, however, attenuates near exponentially with depth due to the  
38 degradation of the particulate material as it sinks (Martin et al. 1987). Bacteria and  
39 zooplankton are believed to be approximately equally important for the remineralization of  
40 sinking particles (Steinberg et al. 2008). Bacteria rapidly colonize sinking particles, facilitated  
41 by their chemotactic behavior (Stocker et al. 2008), and account for a surprisingly constant  
42 carbon-specific degradation rate of ca.  $0.1 \text{ d}^{-1}$  (Ploug and Grossart 2000). This quantitative  
43 understanding of the role of bacteria can readily be incorporated in models of flux attenuation  
44 (Buesseler and Boyd 2009). The contribution of zooplankton to flux attenuation is much more  
45 variable and the underlying processes are poorly known (Steinberg et al. 2008). The lack of  
46 knowledge of zooplankton processes has been cited as one of the main factors hampering the  
47 advances in modeling biogeochemical fluxes (Boyd and Trull 2007).

48       Zooplankton may occur in high abundances on marine snow aggregates in the upper ocean  
49 (Steinberg et al. 1994; Kiørboe 2000), and their grazing on aggregate constituents may be  
50 substantial (Koski et al. 2005). Likewise, large sinking particles may be a significant food  
51 source for many zooplankters (Dagg 1993). It is unclear, however, how the zooplankters find  
52 these particles. Random encounter is an insufficient process to explain observed abundance of  
53 zooplankton on aggregates and remote detection has been invoked to account for the high  
54 densities of zooplankton on snow particles (Kiørboe 2000; Kiørboe and Thygesen 2001;  
55 Jackson and Kiørboe 2004). Bacterial activity on the surface of sinking particles may cause a  
56 substantial leakage of dissolved organic material (Smith et al. 1992), and sinking particles  
57 therefore leave an organic solute trail in their wake (Kiørboe 2001). It has been hypothesized

58 that cruising zooplankters may encounter such trails, which, in turn, may lead the zooplankter  
59 to large, nutritious particles (Kiørboe and Thygesen 2001). Such behavior has been  
60 demonstrated in shrimps (*Acetes sibogae*) that follow scent trails left by sinking food particles  
61 (Hamner and Hamner 1977). Copepods are also known to be able to follow chemical trails.  
62 This has been demonstrated for copepod males in particular that follow pheromone trails left  
63 by receptive females (Doall et al. 1998), but copepodites and females may also be able to  
64 follow artificial trails of amino acids (Kiørboe 2001) or dextrane (Yen et al. 2004).

65 We here test the hypothesis that copepods may find and follow chemical trails left by  
66 sinking marine snow particles. We use discarded appendicularian houses as a source of  
67 particles, as it has been demonstrated that the sinking house leaves a trail in its wake  
68 (visualized in Lombard and Kiørboe 2010, their fig. 3). Discarded houses are an abundant  
69 type of marine snow (Alldredge and Gotschalk 1990) and they may contribute significantly to  
70 carbon export from the surface ocean (Robison et al. 2005). Appendicularian houses are  
71 loaded with, for instance, algae, bacteria and ciliates that are concentrated on houses up to 2-4  
72 orders of magnitude relative to the ambient water (Hansen et al 1996; Lombard et al 2010).  
73 The houses are thus concentrated packages of food, likely to be of a high nutritional value  
74 (similar to its attached particles). Here, we demonstrate that even a typical suspension feeding  
75 copepod (*Temora longicornis*) can feed on sinking marine snow, and that it finds the particles  
76 by following the scent trail that marine snow leave in their wake.

77

## 78 **METHODS**

### 79 ***Origin and culture of animals***

80 Experiments were conducted using both cultivated and freshly collected copepods and  
81 appendicularians ('culture' and 'wild' conditions). Cultured appendicularians (*Oikopleura*  
82 *dioica*) and copepods (*Temora longicornis*), originally collected in the Øresund (56°03'N;

83 12°39'E), western Baltic Sea, were grown in the laboratory (18°C; salinity 35) for > 10  
84 generations following standard protocols (Lombard and Kiørboe 2010). The appendicularians  
85 were fed a mixture of diatoms (*Thalassosira pseudonana*) and phytoflagellates (*Isochrysis*  
86 *galbana* and *Rhodomonas salina*). Under these conditions *O. dioica* produces 7-8 houses d<sup>-1</sup>  
87 (Fenaux 1985). *Temora longicornis* was fed a mixture of *R. salina*, *Thalassiosira weissflogii*  
88 and dinoflagellates (*Prorocentrum minimum* and *Heterocapsa* sp.) in excess, which allowed  
89 for relatively high ingestion and egg production rates.

90 Wild copepods and appendicularians were collected from a pier in the Øresund (55°45' N;  
91 12°35.5' E) 24 h prior to the experiment. Animals were collected with a bucket, which  
92 ensured their good condition. Wild animals were only used for behavioral observations.  
93 Salinity at the time of collection was 17.

94 All experiments were conducted at 18°C.

95

### 96 ***Behavioral observations***

97 We recorded the behavior of *Temora longicornis* in the presence of sinking houses with a  
98 black and white Charge-Coupled Device camera (Watex, WAT-535EX, 25 Hz frame rate)  
99 equipped with a 35 mm lens to yield a field of view of ca. 5 x 4 cm. The experimental arena  
100 consisted of a 500 mL transparent plexiglas chamber (dimensions 5 x 5 x 20 cm). The  
101 chamber was placed in a dark room and illuminated with collimated infrared light from a  
102 light-emitting diode that was shined through the chamber towards the camera. This way  
103 shadow images of copepods and sinking houses were obtained. Both the camera and the light  
104 were mounted on a motorized support which allowed moving the whole system in two  
105 dimensions. Individual particles could thus be followed as they were sinking through the  
106 water column without modifying the settings (size calibration) of the camera.

107 For behavioral observations we used either newly discarded houses (5-10 min), or houses  
108 that had aged for 1-2 h. Fresh and aged houses differ in their properties, because houses  
109 deflate rapidly once discarded. Thus, fresh houses leak internal water and food particles  
110 (Lombard and Kiørboe 2010). Prior to an experiment, the chamber was filled with filtered  
111 water from the appendicularian culture (or freshly collected sea water for wild conditions).  
112 100-200 copepods were then added and allowed 24 h to acclimate. The high density of  
113 copepods was chosen to increase the number of encounter events during the video recordings  
114 and was assumed not to affect the swimming behavior (Dur et al. 2011).

115 Observations were made by gently introducing appendicularian houses (one at a time, up to  
116 15 times) in the surface of the chamber, and then following the sinking house and nearby  
117 copepods with the camera until the house reached the bottom of the chamber (~5 min). Video  
118 sequences were later analyzed using a MatLab script that follows frame by frame the position  
119 of targeted objects. The following parameters were retrieved: sizes, sinking trajectories, and  
120 speeds of appendicularian houses; swimming trajectories and speeds of copepods that reacted  
121 to a house (before and after encountering the chemical plume of the house); and copepod  
122 residence time on the houses. A total of 232 copepod reactions were recorded and analyzed.

123

#### 124 ***Feeding experiment***

125 We estimated the feeding of copepods on discarded appendicularian houses by an indirect  
126 approach, by quantifying the number of fecal pellets that copepods produce when offered  
127 houses. Although dependent on food type, pellet production can be considered to be linearly  
128 related to feeding rate (Besiktepe and Dam 2002). Ten adult *T. longicornis* were incubated for  
129 48 h in 600 mL screw-cap bottles in 0.2- $\mu$ m filtered sea water, containing a variable number  
130 of aged 2-3 mm diameter houses (0; 5; 10; 20; 30; 40; 50 houses per bottle). The highest  
131 tested densities of houses are in the upper end of that observed in nature, representing bloom



132 conditions, where densities of appendicularians (each producing 13-26 houses d<sup>-1</sup>; Sato et al.  
133 2003) may exceed 50,000 m<sup>-3</sup> (Uye and Ishino 1995). All incubations were done in  
134 triplicates. The bottles were mounted on a slowly rotating wheel (1 round per minute) and  
135 incubated in darkness. Water and houses were changed after 24 h and the pellets were counted  
136 at 24 and 48 h. For each counting, the content of the bottles was gently filtered onto a  
137 submerged 10 μm filter and the copepods were immediately transferred to the new water.

138 Pellet production was used to qualitatively verify feeding on houses. Pellet production was  
139 also converted to a crude quantitative estimate of feeding rate, by assuming a pellet volume of  
140  $3.75 \cdot 10^5 \mu\text{m}^3$  (Dutz et al. 2008), a carbon content of 0.052 pg μm<sup>-3</sup> (González and Smetacek  
141 1994), and a carbon assimilation efficiency of 0.75 (Besiktepe and Dam 20020). The obtained  
142 feeding rates should be taken as conservative, since pellets volume and in particular carbon  
143 content are strongly dependent on copepod diet and could be substantially higher than the  
144 values used here (e.g. Ploug et al. 2008). Carbon content of female copepods from our culture  
145 was 7.5 μg C individual (ind.)<sup>-1</sup> (Dutz et al. 2008).

146

## 147 **RESULTS**

### 148 ***Behavioral observations***

149 We observed two different reactions of copepods to sinking houses (see also video A1 in  
150 the Web Appendix [www.aslo.org/lo/toc/vol\\_xx/issue\\_x/xxxxa.xxx](http://www.aslo.org/lo/toc/vol_xx/issue_x/xxxxa.xxx): 1) Direct encounter of a  
151 sinking house by a cruising copepod and subsequent attachment of the copepod to the house  
152 (as shown in video A1). This reaction was observed 86 times. 2) Remote detection and  
153 response to the house: When passing directly above the house the copepod abruptly changes  
154 its swimming direction and accelerates downward towards the house, following the presumed  
155 scent trail (as shown in video A1 and A2). The position where this happens is considered the  
156 detection point. While following the trail, the copepod doubles its swimming speed to 6-8 mm

157  $s^{-1}$  (Table 1, Fig. 1) and swims in a zigzag course towards the particle. Of the 146 cases of  
158 remote detection, the copepods were successful in actually finding and attaching to the  
159 particle in only half of these (72).

160 The positions of detection points (Fig. 1) describe the extension of the chemical trail within  
161 which the concentration of attractant exceeds the threshold for detection and response. The  
162 length of the trail is about 35 mm, corresponding to more than 25 particle radii, its maximum  
163 width about 4 mm, and it is tapered toward its distal part. If the copepod detects the chemical  
164 signal with sensors at the tip of the antennules, then the 'real' width of the plume is 2 x  
165 antennules length ( $\sim 2 \times 0.6$  mm) less than suggested by the detection points, i.e., 2-3 mm. The  
166 width of the plume can alternatively be estimated from the amplitude of the zigzag behavior  
167 ( $\sim 0.7$  mm; Table 1) plus 2 x antennules length; again ca. 2 mm.

168 The probability of detection declines hyperbolically with the distance to the particle (Fig.  
169 2). There was no difference in average detection distance between fresh and aged houses,  
170 whereas there was a difference between the reactions in wild vs. culture conditions. Houses  
171 from wild appendicularians, were detected at a shorter distance by wild copepods than  
172 cultured copepods detected cultured houses (Table 1).

173 Copepods that managed to find a house attached to it and fed intensely from its surface as  
174 evidenced by constant activity of the feeding appendages. Sometimes the copepod would grab  
175 the house with its mandibles and apparently attempt to remove part of the house as evidenced  
176 by vigorous kicking of the swimming legs (*see* the Web Appendix). The copepods resided on  
177 the house for a relatively short ( $< 1$  min) but intense period, which was more than twice as  
178 long for wild than for cultured conditions (Table 1).

179

180 ***Grazing and fecal pellets production***

181 This feeding activity resulted in the production of fecal pellets, and the production of  
182 pellets increased with the concentration of houses. Fitting a Holling Type II response to the  
183 observations yields a saturated pellet production rate of  $34 \pm 13$  pellets ind.<sup>-1</sup> d<sup>-1</sup> (Fig. 3). This  
184 rate was however not reached, even at the highest concentration of houses (83 L<sup>-1</sup>). The  
185 maximum observed pellet production, ca. 15 pellets ind.<sup>-1</sup> d<sup>-1</sup>, corresponds to an ingestion of  
186  $\sim 0.45 \mu\text{g C ind.}^{-1} \text{ d}^{-1}$  (6% body weight d<sup>-1</sup>). The saturated consumption rate of appendicularian  
187 houses would then be about  $0.9 \mu\text{g C ind.}^{-1} \text{ d}^{-1}$  (12% body weight d<sup>-1</sup>), a sufficiently high rate  
188 to support copepod metabolism, while not allowing for a high growth or reproduction rate  
189 (Hernandez-León and Ikeda 2005). Thus even in saturating concentration of houses those only  
190 partly fulfill this copepod needs.

191

## 192 **DISCUSSION**

### 193 ***Chemical or hydromechanical cues?***

194 Our results demonstrate that the copepod *Temora longicornis* is able to remotely detect  
195 sinking appendicularian houses, to subsequently follow the sinking track to the particle, and  
196 eventually to grab the particle and feed on it. To our knowledge, our results constitute the first  
197 demonstration of such particle tracking behavior in a copepod using realistic particles  
198 produced both under laboratory and wild conditions. Similar observations have previously  
199 been reported for planktonic shrimps tracking sinking detritus (Hamner and Hamner 1977),  
200 while the general assumption of the ability of copepods to follow chemical particle trails has  
201 until present been mainly based on theoretical considerations (Jackson and Kiørboe 2004).

202 The detection distance to a sinking 0.25 cm radius house was up to 3.5 cm at a position that  
203 was left by the particle over 25 seconds earlier. This strongly suggests that the cue utilized by  
204 the copepod is chemical rather than fluid mechanical. All our observations correspond to  
205 Reynolds numbers (Re) between 1 to 6. Fluid disturbances at low Re dissipate rapidly due to

206 viscosity; thus, the viscous time scale ( $L^2/\eta$ , where  $L$  is the linear dimension of the disturbance  
207 and  $\eta$  the kinematic viscosity of the water) for a fluid signal of a spatial extension similar to  
208 the size of the sinking particles is  $\sim 6$  s. The fluid disturbance also attenuates spatially, and the  
209 signal generated by the sinking particle at a distance of 3.5 cm can be estimated assuming  
210 Stokes flow for a translating sphere. Using the model developed by (Visser 2001), and  
211 assuming that the fluid velocity signal has to be  $\geq 100 \mu\text{m s}^{-1}$  to be detected (Kiørboe 2011),  
212 the hydromechanical detection distance can be estimated as 0.4 cm; if a 10x smaller detection  
213 signal is sufficient, this estimate increases to 1.2 cm.

214 The behavior of the tracking copepods is consistent with them following a chemical trail. It  
215 resembles the behavior described for males tracking pheromone trails deposited by swimming  
216 females, although tracking velocities observed here ( $< 10 \text{ mm s}^{-1}$ ; Fig. 1, Table 1) are  
217 substantially lower than the swimming speed of female-tracking males of the same species  
218 ( $15\text{-}40 \text{ mm s}^{-1}$ ; Doall et al. 1998) and thus cannot be confused. The constant zigzagging along  
219 the invisible trail has been termed ‘casting behavior’ (Weissburg et al. 1998). It serves the  
220 purpose of constantly checking the radial extension of the trail, and is a prerequisite for being  
221 able to follow the trail. The tracking behavior of the copepods and the weakness of fluid  
222 mechanical disturbances generated by the sinking particles lead us to conclude that the cue  
223 used by the copepod to detect the sinking particle is chemical.

224 The spatial extension of the chemical plume, as evidenced by the distribution of detection  
225 points, is only partly consistent with that predicted from a model that describes the flow and  
226 concentration fields around a sinking sphere that leaks solutes (Kiørboe et al. 2001; *see also*  
227 Fig. 1A). The predicted solute distribution depends mainly on the Péclet number ( $\text{Pe} = aU/D$ ,  
228 where  $a$  is the sphere radius,  $U$  the sinking velocity, and  $D$  the diffusivity of the leaking  
229 substance). The slower the particle sinks, and the higher the diffusivity of the leaked  
230 molecules, the broader the deposited trail. Assuming a diffusivity of  $D = 10^{-5} \text{ cm}^2 \text{ s}^{-1}$ , which is

231 typical for small biological molecules, and the sinking velocities recorded for the discarded  
232 houses (Table 1), we get a Péclet number of about  $10^3$ , and a predicted solute distribution as  
233 shown in Fig. 1A. Obviously, the observed plume is much broader than that predicted, even  
234 when accounting for the length of the antennules of the copepods. The distribution rather  
235 resembles a situation for a Péclet number of order 100 or less (Fig. 1A). We argue that this is  
236 due to a much higher effective diffusivity of leaked substances in our experiments due to the  
237 mixing effect of both the swimming copepods and of the unavoidable convection currents in  
238 the experimental chamber. Observations and theory become consistent with one another if we  
239 assume a 10-fold higher effective diffusivity due to our experimental setup.

240

#### 241 ***Efficiency of particle detection***

242 From our observations, *T. longicornis* has almost twice the chance of remotely detecting a  
243 sinking house rather than directly encountering it (146 vs. 86 observations). However, judged  
244 from the observed ratio of direct collision-encounters to particle encounters facilitated by  
245 remote detection of sinking particles (86 vs. 71), remote detection only has a rather modest  
246 effect on the efficiency by which copepods can find sinking particles. However, we argue that  
247 our experimental design leads to an underestimation of this efficiency due to the mixing  
248 effects of the swimming copepods and small convection currents, but also that we can roughly  
249 quantify the error and estimate the real efficiency from our observations.

250 We use the ‘moving point source model’ of Jackson and Kiørboe (2004) to evaluate our  
251 results. According to this model, the length ( $L$ ), maximum width ( $d$ ; derived from Jackson and  
252 Kiørboe 2004), and cross-sectional area ( $A_0$ ) of the plume can be estimated as

$$253 \quad L = \frac{Q}{4\pi DC^*} \quad (1)$$

254 
$$d = 2.43 \left( \frac{DL}{v} \right)^{0.5} \quad (2)$$

255 
$$A_0 = \frac{0.24}{Dv^{0.5}} \left( \frac{Q}{\pi C^*} \right)^{1.5} \quad (3)$$

256 where  $Q$  ( $\text{mol s}^{-1}$ ) is the rate at which solutes leak from the particle,  $C^*$  ( $\text{mol cm}^{-3}$ ) the  
 257 threshold concentration for detection, and  $v$  ( $\text{cm s}^{-1}$ ) the sinking velocity of the particle.  
 258 Equation 2 allows us to estimate the effective diffusivity of the chemical substance from the  
 259 observed length (3.5 cm) and width (0.2 cm) of the plume and sinking velocity of the particles  
 260 ( $0.05\text{-}0.15 \text{ cm s}^{-1}$ ). The effective diffusivity thus estimated is about  $1\text{-}3 \cdot 10^{-4} \text{ cm}^2 \text{ s}^{-1}$ , one order  
 261 of magnitude larger than the molecular diffusivity of small biological molecules, as also  
 262 proposed above.

263 Kjørboe and Thygesen (2001) and Jackson and Kjørboe (2004) compiled empirical  
 264 evidence to suggest that if the substance to which copepods respond is amino acids, then  $Q$   
 265 ( $\text{mol s}^{-1}$ )  $\approx 10^{-12} a^{1.5}$  and  $C^* \approx 10^{-11} \text{ mol cm}^{-3}$ , where  $a$  is the radius of the sinking particle (0.15  
 266 cm). If we accept these estimates and assume an effective diffusivity of  $1\text{-}3 \cdot 10^{-4} \text{ cm}^2 \text{ s}^{-1}$  then  
 267 the model predicts a plume length in our experiments of 1.67-5 cm, in the range of our  
 268 observations ( $<3.5$  cm). Thus, our experimental observations are internally consistent and  
 269 moreover consistent with independent estimates of particle leakage rates and copepod  
 270 chemical sensitivity.

271 The encounter cross section of the chemical plume can be estimated as

272 
$$A = A_0 + 2SL \quad (4)$$

273 where  $S$  is the length of the antennules (0.6 mm). This may be compared to the encounter  
 274 cross section of the sinking particle itself ( $\pi(a+S)^2$ ) and used to estimate the enhancement in  
 275 potential encounter rate due to chemical signals which are comparable to observed  
 276 enhancement of encounter irrespectively to copepods or houses concentrations. Using the

277 numbers above and a diffusivity not affected by experimental mixing effect, the enhancement  
278 for 2.5 mm diameter sinking houses is about two orders of magnitude. This estimate does not  
279 take into account the decreasing detection probability with increasing distance to the particle  
280 (Fig. 2), and it does not consider the effect of turbulent mixing (Visser and Jackson 2004).

281 One may argue that the starved copepods used in our experiments were particularly  
282 responsive to food signals. As food in the ocean tends to be patchily distributed (Mitchell and  
283 Fuhrman 1989) and as starvation tolerance of neritic copepods such as *Temora longicornis* is  
284 limited (Koski and Klein Breteler 2003), an increased ability of starved copepods to detect  
285 food signals would be a relevant trait. However, our study was not designed to investigate the  
286 effect of starvation on behavior, but simply to demonstrate that chemical plumes behind  
287 sinking particles may significantly increase the possibility for zooplankters to find these  
288 nutritious particles.

289

### 290 ***Feeding on sinking particles***

291 Jackson and Kiørboe (2004) explored the potential for zooplankters to find and feed on  
292 large sinking particles using the above model and parameter values consistent with those  
293 estimated here. While copepods are generally thought of as microphageous that mainly feed  
294 on microscopic phytoplankton and protozoans, the analysis of Jackson and Kiørboe (2004)  
295 suggested that large sinking particles may also be an important source of nutrition. The  
296 importance of sinking particles in the nutrition of zooplankton has also been suggested based  
297 on the metabolic demands of the zooplankton communities in the mesopelagic zone  
298 (Steinberg et al. 2008) and analysis of their gut fatty acid and pigment compositions (Wilson  
299 and Steinberg 2010).

300 The residence times of the copepods on the houses are short, consistent with earlier  
301 laboratory observations (Alldredge 1972). Reported residence times vary from minutes for

302 pelagic organisms (Shanks and Walters 1997) to hours for semi-benthic species (Koski et al.  
303 2005). It has been suggested that the short residence times are the result of a trade-off between  
304 the good feeding conditions and the elevated predation risk when attached to an aggregate,  
305 and that a copepod should remain on the aggregate only long enough to fill its gut (Kiørboe  
306 and Thygesen 2001). From estimated house encounter rates (calculated from observed  
307 copepods swimming speed, and sizes of particles and chemical trail) and consumption for *T.*  
308 *longicornis*, one can estimate that each house encounter leads to the ingestion of 3-5  $10^{-4}$   $\mu\text{g}$   
309 C, and an ingestion rate during attachment of 0.1-0.2  $\mu\text{g C h}^{-1}$ . This is a very high  
310 instantaneous ingestion rate, but it would still take a copepod about 7-15 min to fill its gut  
311 (assumed to be the equivalent of one fecal pellet).

312 Our observations show that *T. longicornis* feed on discarded houses but even saturated  
313 feeding rates are only 10% of those reported for grazing on phytoplankton (Besiktepe and  
314 Dam 2002). The feeding rates ( $\sim 4 \times 10^{-4}$   $\mu\text{g C encounter}^{-1}$ ) extrapolated to natural  
315 concentrations of discarded appendicularian houses (e.g., max. 6  $\text{L}^{-1}$  in the North Sea; Koski  
316 et al. 2007; encounter rate calculated with a normal case of effective diffusivity) would be  
317 low, around 0.5  $\mu\text{g C ind. d}^{-1}$ . However, appendicularian houses are only one example of  
318 sinking particles, and copepods may also feed on other types of marine snow, such as diatom  
319 flocks or fecal pellets. Further, the feeding rates observed in the laboratory may underestimate  
320 those in the field. As suggested by the difference between cultured and wild copepods in our  
321 experiments, the wild copepods are more efficiently feeding on appendicularian houses. This  
322 may be due to the immediate history of the animals, e.g., hunger level or age, body size, or the  
323 different behaviors of the cultured and wild copepods (Tiselius et al. 1995).

324 *T. longicornis* is probably not a typical aggregate feeder and other zooplankters have  
325 morphologies and behaviors that make them particularly adapted to feed on marine snow  
326 aggregates. Copepods that are typically found on marine snow aggregates are harpacticoids,



327 such as *Microsetella norvegica*, and copepods of the genus *Oncaea* (Shanks and Walters  
328 1997). These species are not able to feed efficiently on suspended food, but are dependent on  
329 aggregates for feeding (Koski et al. 2005), and behavioral observations suggest that they  
330 readily feed on appendicularian houses (Ohtsuka and Kubo 1991). *M. norvegica* and semi-  
331 benthic harpacticoids can have feeding rates ranging from 40% to 200% body weight<sup>-1</sup> d<sup>-1</sup> on  
332 appendicularian houses and settled diatoms (Koski et al. 2005; Koski et al. 2007), thus being  
333 considerably more efficient in aggregate feeding than *T. longicornis*.

334 Published estimates of the effect of copepods on the attenuation of sinking flux suggest  
335 potentially high degradation rates both in and below the euphotic zone, mainly depending on  
336 the abundance of potential grazers (Kiørboe 2000; Koski et al. 2005; Steinberg et al. 2008).  
337 Calanoid copepods, like *Temora longicornis*, are not normally considered feeders on large,  
338 sinking particles, and the feeding rates found here were lower than typically observed for *T.*  
339 *longicornis* feeding on suspended food (e.g., diverse phytoplankton). However, the  
340 degradation of sinking aggregates due to zooplankton grazing may be intense if typical  
341 detritivorous zooplankton exhibit similar aggregate-finding behavior as that reported here for  
342 *T. longicornis*. As calculations based on the abundance of some copepod species (typically  
343 *Microsetella norvegica* and *Oncaea* spp.) on marine snow suggest that random encounter is  
344 not sufficient to explain their high concentrations on aggregates (Kiørboe 2000), this seems  
345 likely. An efficient mechanism to find and colonize particles, together with their at times high  
346 abundances (up to 100 ind. L<sup>-1</sup>; Uye et al. 2002), suggest a potentially high effect of particle-  
347 colonizing copepods on the attenuation of vertical flux.

348 We have here demonstrated a mechanism by which copepods may locate sinking marine  
349 snow aggregates. This mechanism may account for the high abundances of copepods  
350 observed on aggregates, and is consistent with copepods contributing significantly to the  
351 vertical attenuation of particle flux in the ocean. Our observation is one step further in

352 understanding the controls of flux attenuation and suggests that remote detection of chemical  
353 cues can enhance the encounter and degradation rates by orders of magnitude from what  
354 would be predicted based on the particle sizes and concentrations alone.

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## Tables

Table 1 : Summary of copepod reactions to sinking aggregates at the different experimental conditions: Total number of observations ( $n$ ), number of direct encounters, number of chemical tracking events (including copepods that lose the trail), mean house size and sinking speed, reaction distance of the copepods to the sinking house, mean zigzag amplitude, residence time, and swimming velocity before and after encountering the chemical trail ( $\pm$  SD). Differences between new and old houses have been tested as no significantly different for all observations ( $t$ -test,  $p > 0.05$ ) except houses size ( $t$ -test,  $df = 230$ ,  $p < 0.001$ ). Differences between ‘wild’ and ‘cultured’ conditions are significant with respect to detection distance ( $t$ -test,  $df = 148$ ,  $p < 0.001$ ), residence time ( $t$ -test,  $df = 110$ ,  $p = 0.012$ ) and swimming and tracking velocities ( $t$ -tests,  $df = 109$ ,  $p = 0.048$  and  $df = 108$ ,  $p < 0.001$ , respectively).

Observation conditions	$n$	Encounter		House size (mm)	House sinking speed (m d <sup>-1</sup> )	Mean reaction distance (mm)*	Mean zigzags amplitude (mm)	Time on particle (s)	Copepods speed (mm s <sup>-1</sup> )		
		direct	chemical (lose)						before encountering the trail	following the trail*	
culture	new	127	50	77 (37)	3.5 ( $\pm$ 0.8)	129	12.7 ( $\pm$ 8.3)	0.78	11.0 ( $\pm$ 22.3)	4.1 ( $\pm$ 1.8)	7.5 ( $\pm$ 1.4)
	old	35	13	22 (9)	2.4 ( $\pm$ 0.3)	132	12.3 ( $\pm$ 9.8)	0.62	12.9 ( $\pm$ 17.4)	4.4 ( $\pm$ 1.9)	8.0 ( $\pm$ 2.3)
	total	162	63	99 (46)	3.3 ( $\pm$ 0.9)	130	12.6 ( $\pm$ 8.7)	0.75	11.3 ( $\pm$ 21.6)	4.2 ( $\pm$ 1.8)	7.6 ( $\pm$ 1.6)
wild	new	33	13	20 (12)	3.5 ( $\pm$ 0.4)	48	7.9 ( $\pm$ 5.6)	0.56	23.2 ( $\pm$ 16.6)	3.6 ( $\pm$ 1.4)	6.3 ( $\pm$ 1.2)
	old	37	10	27 (16)	2.8 ( $\pm$ 0.5)	57	8.6 ( $\pm$ 6.6)	0.62	27.7 ( $\pm$ 26.7)	3.5 ( $\pm$ 1.5)	6.5 ( $\pm$ 1.6)
	total	70	23	47 (28)	3.1 ( $\pm$ 0.6)	54	8.3 ( $\pm$ 6.2)	0.60	26.1 ( $\pm$ 23.7)	3.5 ( $\pm$ 1.5)	6.5 ( $\pm$ 1.5)

\* only consider chemical reactions



472 **Figure legends**

473 Figure 1 : (A) Relative position of *Temora longicornis* when it reacts to the chemical trail left  
474 by sinking discarded house (represented here as a large dot). The two inserted images  
475 represent the theoretical chemical plume assuming two different Péclet numbers (adapted  
476 from Kiørboe et al. 2001). (B) Example of *T. longicornis* swimming pattern and speed (mm s<sup>-1</sup>)  
477 relative to position of sinking discarded houses. The detection point is marked with a black  
478 arrow. Note the increased speed and the zigzagging behavior when following the chemical  
479 trail.

480

481 Figure 2 : Frequency distribution of detection distance of *T. longicornis* to the sinking  
482 aggregates. Wild and culture conditions were plotted separately since they were tested as  
483 significantly different ( $\chi^2$ -test  $p > 0.05$ ).

484

485 Figure 3 : *T. longicornis* fecal pellet production when offered discarded house at different  
486 concentrations (number L<sup>-1</sup>). Error bars represent the standard error originating from  
487 triplicates. Relationship is:  $Y = 33.8 (\pm 13.0)X / (X + 133 (\pm 73))$  ( $R^2 = 0.84$ ;  $n = 27$ ) dotted lines  
488 represent the 95% confidence limits intervals of this relationship.

489

## Figures

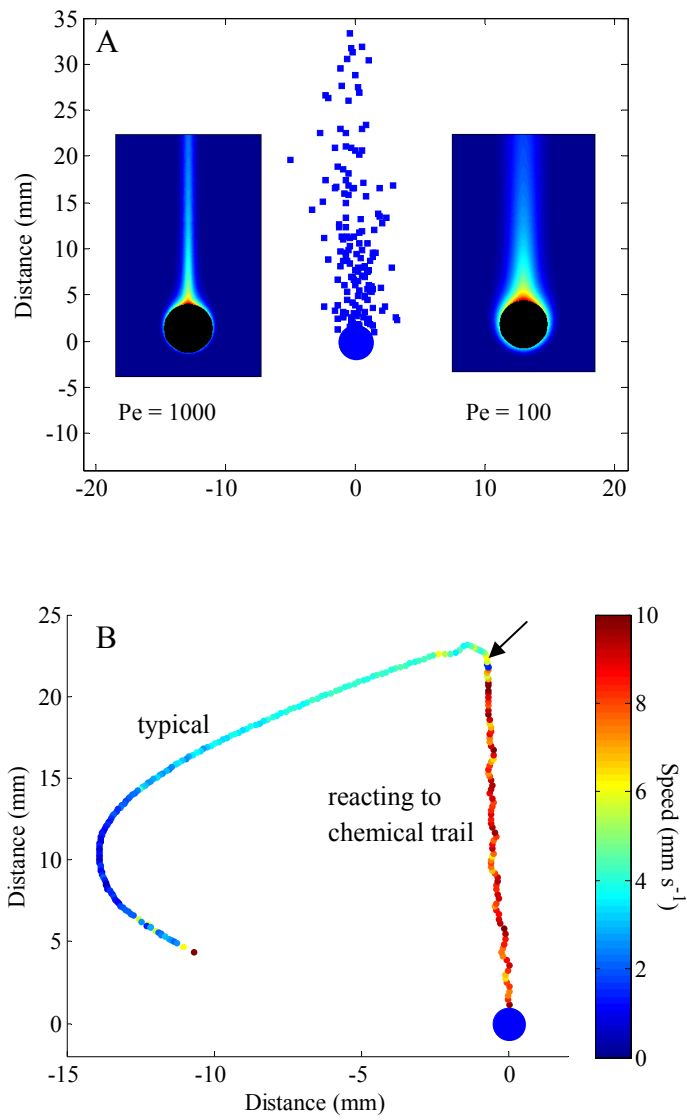


Figure 1

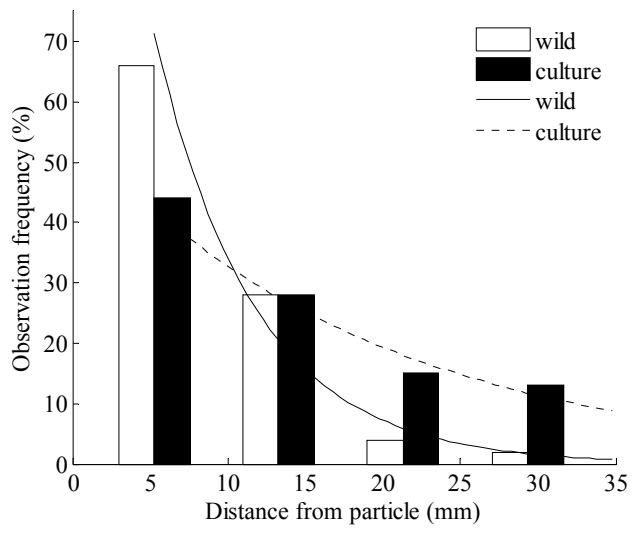


Figure 2

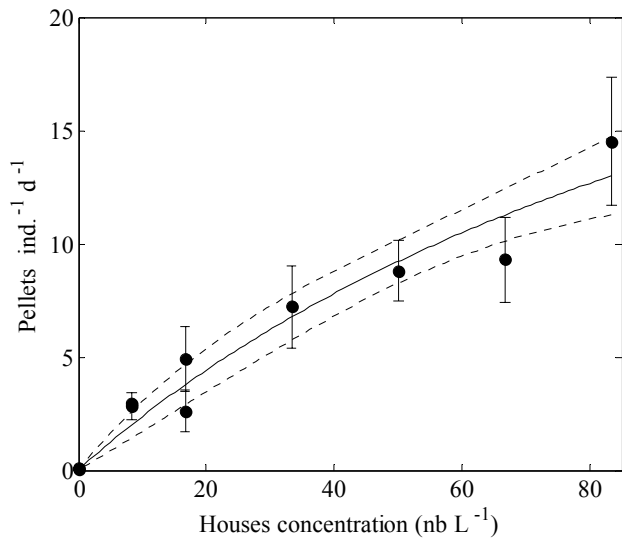


Figure 3

## Web appendix

These three video sequences illustrate the different behavioral observations described in the accompanying manuscript.

Video A1: Example of *Temora longicornis* interacting with sinking marine snow (discarded appendicularian house) using infra red light. All the different behavior (chemical trail detection, direct encounter) are illustrated.

Available online at:

<http://fabien.lombard1.free.fr/temoratrackIR2.wmv>

Video A2: Example of *T. longicornis* following a chemical trail left by a sinking marine snow (discarded appendicularian house) using white light illumination inside a rotating tank:

<http://fabien.lombard1.free.fr/temoratrackwhiteligth.wmv>

Video A3: Close-up view of the feeding behavior of *T. longicornis* on marine snow (discarded appendicularian houses) using a binocular lens (inside a petri dish).

Available online at

<http://fabien.lombard1.free.fr/closeupfeeding.wmv>