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Use of the Underwater Video Profiler for the Study of Aggregate Dynamics in the North Mediterranean

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The Underwater Video Profiler is a vertically deployed survey system designed for the quantification of particles >280 µm and of large zooplankton in the 0–1000 m water column. Light reflected by undisturbed target objects forms a dark-field image, which is recorded at 25 Hz frequency. The recorded images are automatically digitized and analysed. The results are expressed as abundance or size distributions and they can be converted to volume or mass units. The system can be configured as a multi-instrument array and can simultaneously acquire biological and physical data. From May 1994 to April 1995 a monthly survey was performed across a frontal structure associated to the North Ligurian geostrophic current. In winter and spring 1995 the front, as well as the offshore dispersion limit of particles, were located near to the coast. In contrast, during autumn 1994, its position was open sea and the terrestrial matter was dispersed far from the coast. The continuous presence of intermediate nepheloid layers along the continental slope indicates that different processes may supply and transport the particulate matter to deeper layers, from where it can be diffused into the basin.

Keywords: Underwater Video Profiler; aggregates; organic matter, geostrophic front; nepheloid layers; Mediterranean

Introduction

Aggregates >280 µm are ubiquitous components of the ocean water column. They are unique micro-habitats where decomposition and regeneration of nutrients occur at high rates (Alldredge & Silver, 1988). These aggregates form a large part of the particulate organic matter pool and mediate the surface-derived matter to the ocean's interior and to the sea floor (Fowler & Knauer, 1986). Their friable nature precludes their regular capture and subsequent laboratory study.

Commonly used non-optical methods allow neither the estimation of size of large aggregates, nor the estimation of their vertical distribution in the water column. These methods are based either on *in situ* filtration (Bishop & Edmond, 1976; Wakeham & Canuel, 1988) or on the onboard filtration of water bottle samples. They alter the fragile particles and integrate all size classes into a single size fraction. In addition, the number of sampled layers is limited.

Recently, several *in situ* still or video camera systems were built to complement the usual methods of sampling. They were used to produce abundance and size profiles of particles (Honjo *et al.*, 1984; Gardner & Walsh 1990; Asper *et al.*, 1992, Gorsky *et al.*, 1992; Davis & Pilskaln 1993; MacIntyre *et al.*, 1995) and of marine organisms (Davis *et al.*, 1992; Olney and Houde 1993; Lenz *et al.*, 1995; Fabricius & Wolanski, 2000; Gorsky *et al.*, 2000). These systems revealed the heterogeneous spatial distribution of large aggregates. Jackson *et al.* (1997) studied the particle size spectra between 1 µm and 1 cm in Monterey Bay, using six different instruments. They found that most of the particulate mass was contained in the 0·1–3 mm range and that this may have important implications for the studied environment. The organisms living in and on aggregates should form an important part of the plankton ecosystem, aggregating small particles and breaking down preferentially larger ones. Alldredge (1998), showed that the size-specific POC, PON and mass content of different marine snow aggregate types in superficial waters is similar. This similarity indicates that C and N content of marine snow can be estimated from the size and abundance profiles obtained by the *in situ* camera systems.

In this paper we describe the new vertical profiler for the study of marine aggregates >280 µm and present results on a one year seasonal survey performed in the north-western Mediterranean.

Full sized figures, tables and animations are stored on the CD-ROM accompanying this article. Use a Web browser to access the start page 'default.htm' and follow the links. The help file 'help.htm' provides answers for some common problems.

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Material and methods

The Underwater Video Profiler (UVP) was constructed in the Laboratoire d'Océanographie Biologique et d'Ecologie du Plancton Marin in Villefranche sur mer, France (UPMC/CNRS) with the support of the CNRS (Centre National de la Recherche Scientifique) and the European MAST II and III programmes. The UVP has been developed for the acquisition of large-particle (>280 μm) abundance and size distribution data from 0 to 1000 m (smaller size class estimations and 0–2800 m working range can be attained with slight modifications of the existing equipment).

The UVP is composed of a waterproof, vertically deployed multi-instrument array for *in situ* image and environmental data acquisition and of a system allowing the analysis of images and the treatment of data.

The moored equipment

Three models of the UVP have been constructed since 1990 (Gorsky *et al.*, 1992). They were designed to minimize the disturbance of the illuminated volume in order to reduce a possible disruption of imaged particles. All models are autonomous and can be lowered on a hydrological cable. Here the third model is presented.

The UVP model III (Animation 1) is a vertically lowered instrument mounted on a galvanized steel frame (1·1 × 0·9 × 1·25 m). The lighting is based on two 54W Chadwick Helmuth stroboscopes. Two stainless steel mirrors spread the light beams into a structured 10 cm thick slab. The strobes are synchronized with two Exavision XC 644 black-and-white CCD video cameras with 12 and 6 mm C-mount lenses. The illuminated particles in a volume of respectively 1·3 and 6·5 l are recorded simultaneously onto two Hi8 recorders. The cameras are positioned perpendicular to the light slab and only illuminated particles in dark background are recorded (Animation 2). The short flash duration (pulse duration = 30 μs) allows a fast lowering speed (up to 1·5 m s^{-1}) without the deterioration of image quality. Instead of the stroboscopes, four 100 W spotlights can be used for continuous observations of a larger non-structured water volume (Animation 3). In this case the lowering speed is slower. Depth, temperature and conductivity data are acquired using a Seabird Seacat 19 CTD probe with fluorometer and nephelometer (both from Chelsea Instruments Ltd.). The system is powered by four 24V batteries and is piloted by a Texas 370 microprocessor. The data acquisition can be time or depth related and programmed prior to the immersion. Daylight brightness can interfere with the imaging of particles in the upper 20–30 m. This problem can be minimized using red filtered illumination (Davis *et al.*, 1992).

The UVP is well adapted to count and measure fragile aggregates such as marine snow as well as delicate zooplankton. For reliable assessment of macrozooplankton, a programmed repetitive profiling option is available.

Image analysis

The UVP has two important features: (a) it does not disturb the recorded particles or organisms and (b) it allows quick data retrieval and processing. Processing of images obtained by the UVP in the structured light beam is automated. Onboard, a rapid image analysis is carried out at a rate of five or more images per second (depending on the computer specifications). The recorded profile is digitized without compression using a Matrox frame grabber (512 × 512 × 256 pixel matrix). The images are analysed and treated automatically by custom-made software. The algorithm utilizes a pixel-intensity threshold and a 3 pixel, minimum area criteria. Objects >3 pixels in each image are detected and enumerated. The area and maximum length of every individual object is measured. Data are stored in an ASCII file and can be combined with the associated CTD, fluorometer and nephelometer data using a spreadsheet software. Vertical profiles can be printed out onboard, approximately 30 min after the recovery of the UVP.

The complete profile, consisting of approximately 25 000 images (0–1000 m profile at a 1 m s^{-1} lowering speed and at the acquisition rate of 25 images s^{-1}) is treated in the laboratory by two custom built programmes. The first, written in Visual C++ (Microsoft), digitizes the images from a Hi8 player at normal speed and without compression and stores the digitized images on a RAID drive (RAID—Redundant Array of Independent Discs). The four hard discs composing the RAID drive are presented to the operating system as a single one. Once all the images digitized, the software enumerates the number of objects in each frame, extracts their attributes, and stores their values in an ASCII file. The second software (MATLAB, Scientific Software) is used for data treatment and presentation (Figure 1). It allows to obtain cumulative size spectra in the chosen depth layers, groups particles into distinct size groups and visualizes their evolution (Stemmann *et al.*, in press).

Calibration

The calibrations were carried out in a dark test tank filled with 3 m^3 filtered (0.8 µm) seawater. The brightness measured in the test tank was similar to that in the aphotic layers. A calibration grid, placed at different depths of the light slab, was used to estimate the recorded water volume. The dimensions and volume of the parallel light beam recorded by the 12 mm and the 6 mm cameras are 131·6 × 125 × 95 mm representing 1·33 l, and 288·5 × 264·7 × 99·25 mm representing 6·51 l respectively. The pixel–mm relationship was calibrated in the same test tank by injection of biological particles (range 90 µm–20 mm) measured prior to their use with a stereomicroscope (Figure 2). The results indicate that the tested configuration can detect 280 µm-sized particles and can reliably measure particles larger than 460 µm in diameter. The metric surface as a function of the pixel surface for the 12 mm and 6 mm lens cameras can be expressed by the following equations:

$$12\ \text{mm} : Y = 0{\cdot}02 \times 1{\cdot}137,\ R^2 = 0{\cdot}873;$$
$$6\ \text{mm} : Y = 0{\cdot}008 \times 1{\cdot}556,\ R^2 = 0{\cdot}828.$$

Bodies of zooplankton might be recorded and considered as particles. We analysed and compared zooplankton profiles with profiles of particles at the studied site (Stemmann *et al.*, in press). The number of living organisms was found to be one or two orders of magnitude lower than that of large non-living particles.

Field sampling

The vertical distribution of large aggregates and hydrographic parameters in the 80–1000 m water column were determined along a coast-open sea section (MBP in Figure 3) off Nice, France, from May 1994 to April 1995 (Figure 3). The sampled site is known for its permanent frontal structure, created by a geostrophic current system (Boucher *et al.*, 1987; Gorsky *et al.*, 1991; Sammari *et al.*, 1995). Data was taken as part of the MBP Front programme (JGOFS-France) to study the particle abundance and size spectra in the northern Mediterranean (Stemmann, 1998). Eleven stations distanced by 2·5 miles were sampled every month on board of RV *Korotneff*, *Tethys II* and *G. Petit*. The sampling of one section was carried out during daylight and within one or two days, depending on atmospheric conditions and the duration of the daylight period. On board, 50 kHz echosounders (Koden CVS 8805/T Koden Marine Electronics and Simrad AS) were used to avoid the sampling during vertical migration of zooplankton.

Results

Twelve contour plots of the studied section are presented in Animation 4. They show the abundance distribution of large particles from May 1994 to April 1995. The excess density is represented by the 28·85, 28·95 and 29·04 isopycnals (continuous, discontinuous and dotted lines respectively). The abundance of particles varies from 0 to 5 particles per litre to more than 80 particles per litre. Their size distribution is only briefly discussed here (Figure 1). The detailed results will be published elsewhere.

In May 1994 the frontal zone was found from 10·5 to 25·5 miles offshore. The density gradient was weak and the distribution of particles followed that of the isopycnals. The highest abundance of particles was confined near the continental slope and down to a depth of 400 m. The overall distribution of particles in the water column was patchy. The small size classes were observed near the slope, whilst the larger particles were found in the open sea under the divergence. The 14 °C isotherm located at the depth between 20–30 m separated a shallow surface layer from the rest of the water column.

In June 1994 the frontal zone was located between 3 and 13 miles offshore. The coastal nepheloid layer reached a depth of 900 m, but did not extend offshore beyond the frontal zone. In contrast to the previous month, larger aggregates were localized near the slope where the total abundance was high. The 14 °C isotherm was situated at depths between 30 and 40 m.

The superficial stratification in July 1994 was well marked. The 14 °C isotherm was situated between 40 and 50 m. The frontal zone was located between 15·5 and 20·5 miles offshore. The distribution of particles in the studied water column was patchy with mid-, and deepwater maximums near the slope and offshore. In the superficial layer it followed the isopycnals. High aggregate concentrations were found at the open sea stations.

In August 1994, the abundance distribution of particles showed a typical summer situation, with higher concentrations of large particles near the continental slope and low standing stock of the particulate matter in the water column offshore. Between 80 and 400 m, particles were larger than in the deeper layers. The frontal structure was weak, and the front was located between 10 and 20 miles offshore. The 14 °C isotherm was situated between 50 and 60 m.

The frontal structure remained weak in September 1994, but the concentration of aggregates increased near the continental slope, forming several patches. In the open sea their density remained low but the

particles were larger in the superficial and mid-water than in the deep layers. The stratification was comparable to the one in August with the 14 °C isotherm at 60 m depth.

In October 1994 the front was located between 10·5 and 18 miles offshore. The 14 °C isotherm was found deeper than during the preceding months, between 70 and 80 m. The sub-superficial particles concentration maximum (between 100 and 150 m) extended to 10·5 miles offshore. Beyond 700 m the nepheloid layer reached distance of 15·5 miles offshore. Large particles were found in the entire water column except in the deep open sea layers (below 500 m and beyond 15·5 miles offshore).

November 1994 was characterized by a weak frontal structure, deep 14 °C isotherm (80 m) and three high concentration patches of aggregates along the continental slope (between 100–150, 200–280 and 500–600 m). Larger size classes dominated the section.

In December 1994, the frontal zone showed an open sea position. It was located between 15·5 and 25·5 miles offshore. The pycnocline remained marked and deep. An important nepheloid layer was observed beneath the depth of 280 m extending as far as 25 miles offshore. The highest concentration of large particles was observed between 10·5 and 15 miles offshore.

In January 1995, the front was situated closer to the coast than in December 1994 (between 13 and 20·5 miles) and the density gradient was steeper. The water column was vertically mixed and a weak fluorescence signal was measured offshore at the surface. The upper coastal nepheloid layer followed the contour of the 28·5 isopycnal. In the deeper strata the nepheloid layer extended to the open sea but with aggregate concentrations much lower than in December. Abundance of large particles in the water column remained high.

In February 1995, the front was located near the coast extending from 5 to 18 miles offshore. The fluorescence increased in the upper 20 m. The upper nepheloid layer was constrained between the coast and the 28·5 isopycnal. In the deeper strata aggregates were less abundant than in January but they belonged mainly to large size classes.

In March 1995 the frontal zone was situated near the coast, between 3 and 10 miles. Two fluorescence maximums were observed. The first one between 8 and 18 miles, reached a depth of 100 m. The second one was superficial, and was located further offshore corresponding to the location of the upwelled water. The upper and lower nepheloid layers remained near the slope and a shift toward smaller size classes was observed in the water column.

In April 1995 the frontal zone remained coastal, between 3 and 13 miles and the superficial fluorescence layer was about 40 m thick. Two abundance maximums of aggregates were observed. The first was located along the isopycnal slope (below the depth of 280 m), the second below the divergence. The former was composed of larger particles than the latter.

Discussion

Methodology

While *in situ* camera systems do not provide the possibility to study the chemistry of aggregates, they do yield a rapid survey of their distribution and allow the study of aggregate dynamics near the continental margins and in the open sea. From size measurements it is possible to calculate the mass concentration of particles and thus evaluate their importance in the transport of elements in the sea. With the addition of environmental sensors, biological phenomena can be studied and quantified together with physical and chemical processes.

The method presented here is innovative in the sense of (a) the high frequency image acquisition (25 Hz), that allows the detection of small scale patches (of tens of cm in size, Animation 3); (b) the rapid image analysis and data treatment. Onboard, a 0–1000 m profile is printed out 30 min after the recovery of the UVP and may be used for the determination of a subsequent sampling strategy; (c) the self-contained design that allows the UVP to be used on virtually any vessel longer than 20 m equipped with a crane; (d) the simultaneous study of aggregates and of macrozooplankton (cf. Gorsky *et al.*, 2000).

When compared to the existing systems the originality of the UVP consists in its exhaustive quantification of large aggregates and in rapid and autonomous data treatment. The double camera system increases the studied size spectrum. The points which will be improved are: (a) the definition, that is lower than the one obtained by photographic methods and (b) the sampling volume that is relatively small for the quantification of the macrozooplankton. We did not develop a software for the recognition of faunistical groups, since the UVP was principally dedicated to the quantitative study of marine aggregates.

Aggregate dynamics

According to Alldredge (1998), marine snow aggregates are formed by repetitive collision and adhesion of smaller particles. These collisions result from physical processes of fluid shear or differential settlement.

A number of small particles of different origins compose one large particle. The size–mass relationship is therefore likely to be similar for different types of aggregates. Along the superficial discontinuities layers particles accumulate within hours (MacIntyre *et al.*, 1995) but the fate of this matter and its layering in deeper strata is unknown. Using the UVP during the MBP Front time-series study, it has been demonstrated that seasonality as well as several physical, biological and mixing events strongly influence the spatial distribution of large aggregates in the water column. Here the influence of the attached and free living fauna in marine snow dynamics was not studied because the time scale of their activity was much shorter than our sampling period. According to Lampitt *et al.* (1993) it varies from hours to days and thus, this fauna can play an important role in the diel variability of the particle pool, not considered here.

On the studied section, in 1994/95, the following main features influenced the spatial distribution of large aggregates.

Frontal structure. The frontal density gradient associated to the coastal geostrophic current (Boucher *et al.*, 1987) plays an important role in the spatial distribution of the large particles in the upper 280 m in the Ligurian sea. When the density gradient is strong and located near the coast, it constrains the dispersion of particles and of zooplankton (Pedrotti & Fenaux, 1992) seawards. This was the situation in winter and spring 1995. In addition, the primary production enhanced by upwelled nutrients fuels the production of particles, which are transported along the isopycnal slopes from superficial layers to intermediate depths.

Winter vertical mixing. The vertical mixing of superficial cold water transports slowly sinking particles trapped in this water mass rapidly to deeper layers. The mixing process may play an important role in re-distribution of the suspended matter in the water column. It has been observed that large particles dominated the water column from December until March.

Near slope midwater nepheloid layer formation. Nepheloid layers near slope were always observed, suggesting that the coastal current system continuously re-suspends deposited material. The continental shelf in the studied zone is narrow and the slope is steep. Thus, the terrestrial input can rapidly enrich these layers. Another source of the aggregates is the Ligurian current itself, carrying terrestrial matter from different coastal zones.

Local biological activity. The primary production increases from January until May and is exported vertically, as rapidly sedimenting dense aggregates, compacted mainly by zooplankton grazing activity or along the isopycnals when the sinking of small and porous matter is slow.

Post-bloom and summer depletion. From May till August 1994 the distribution of the particulate matter in the entire water column was patchy. The stratification became marked and the photosynthesized matter was exported from the euphotic zone or was depleted via grazing or regeneration.

Autumnal increase. During autumn 1994, from September to December, a constant increase in the concentration of the particulate matter was observed in the water column. The rainfall during this period was correlated with the increase in the concentration of suspended particulate matter. The extended midwater layer in December was observed two weeks after strong floods due to heavy rainfall (Figure 1). Thus, terrestrial input can reach deep layers as far as 30 miles offshore.

In situ imaging instruments such as the UVP presented here are particularly adapted for the study of the spatial and temporal distribution of large and fragile aggregates and organisms in the water column. They can be useful for small and mesoscale and time series studies. Coupled with different probes, the user can expect a coherent and detailed description of the studied structures. The non-destructive data acquisition and rapid data processing of biological and physical variables show a great potential for this methodology in modern oceanographic research.

Acknowledgements

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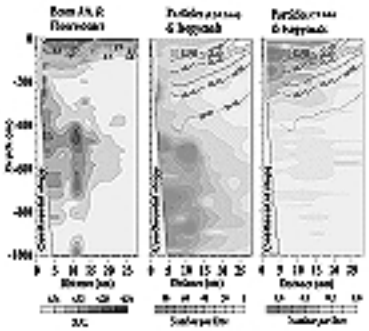


FIGURE 1. Distribution of particles in the slope/open sea section between 80–1000 m depth off Nice, France, in December 1994. Comparison between the beam attenuation data obtained using a transmissometer (SeaTech) coupled to the UVP, and the distribution of two size classes (<0·5 mm and >1 mm) of particles obtained by the UVP. Chlorophyll concentrations are in green, isopycnals in blue. R.U.: relative units, nm: nautical miles.

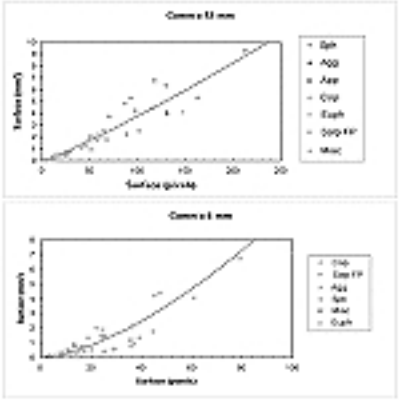


FIGURE 2. The relationship between particle surface in pixels and in mm^2 measured in a test tank. Agg: mucous particles (medusa fragments, appendicularian houses), App: trunk of oikopleurid appendicularians, Cop: preserved copepods, Euph: euphausiid furcilia stages, Salp FP: salp fecal pellets, Sph: spherical gelatinous particles, Misc: miscellaneous aggregates. The metric surface as a function of the pixel surface for the 12 mm and 6 mm lenses is expressed by: 12 mm: $Y=0{\cdot}02 \times 1{\cdot}137$, $R^2=0{\cdot}873$; 6 mm: $Y=0{\cdot}008 \times 1{\cdot}556$, $R^2=0{\cdot}828$.

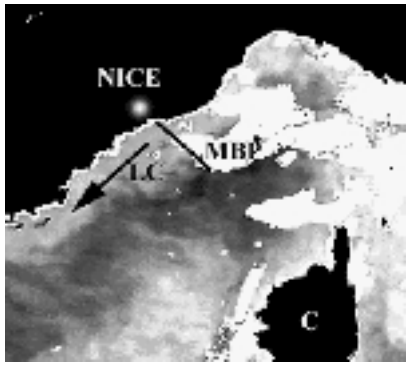
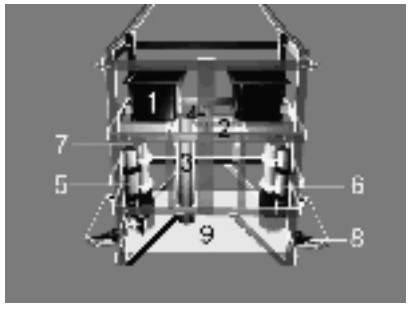
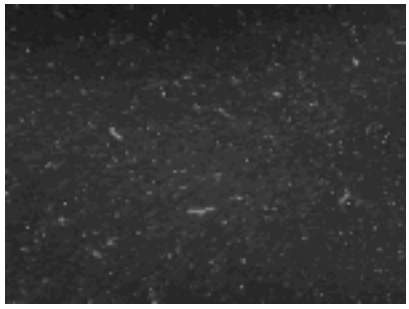


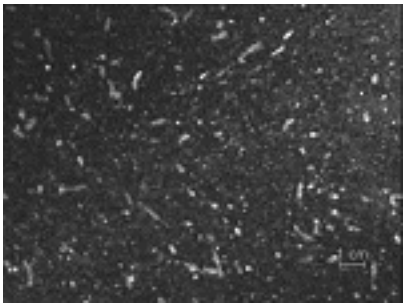
FIGURE 3. December 1994 NOAA/AVHRR SST image of the study site (courtesy of DLR/DFD, Oberpfaffenhöfen). LC: Ligurian current, MBP: the sampled section during the MBP Front programme, C: Corsica island. Dark brown: warm waters, light brown: colder waters.



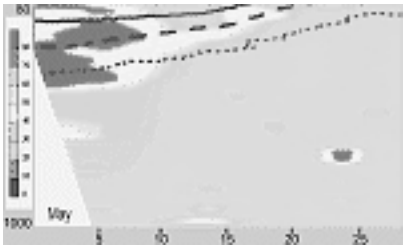
ANIMATION 1. The Underwater Video Profiler. 1: 24 V power supplies; 2: watertight container with two Hi8 recorders and synchronization electronics; 3: CTD; 4: video cameras; 5: nephelometer: 6: fluorometer; 7: stroboscopes; 8: spot lights; 9: the structured light slab (for details see text).



ANIMATION 2. Composite video sequence. Part 1: Sequence in the chlorophyll maximum zone viewed by spotlights showing no perturbation due to system design; part 2: real speed record of particles in the structured light slab; part 3: slow motion representation of particles in the structured light slab.



ANIMATION 3. Small scale patchiness of phytoplankton aggregates. The sequence represents the distribution of large aggregates from 49 m to 58·5 m depth in the Alboran Sea (Mediterranean). The layer of maximum aggregate density is about 40 cm thick.



ANIMATION 4. Monthly distributions of particles in the coast/open sea section between 80–1000 m depth (Y-axis) off Nice, France. The sampled period showed here, started in May 1994 and ended in April 1995. The isopycnals (continuous, discontinuous and dotted blue lines) represent respectively the 28·85, 28·95 and 29·04 density excess ($kg\ m^{-3}$). Distances are given in nautical miles. The concentration of particles (in number of particles per litre) increases from deep blue (minimum) to red (maximum). The colour scale is shown near the Y-axis. Values shown here represent 5 m averages. White triangle = continental slope.