Ocean Sci. Discuss., 10, 1367–1404, 2013
www.ocean-sci-discuss.net/10/1367/2013/
doi:10.5194/osd-10-1367-2013

Ocean Science
Discussions
Open Access

Temporal variations of zooplankton biomass in the Ligurian Sea inferred from long time series of ADCP data

R. Bozzano[1], **E. Fanelli**[2], **S. Pensieri**[1], **P. Picco**[2], **and M. E. Schiano**[1]

[1] National Research Council of Italy (CNR-ISSIA) – Via de Marini 6, 16149, Genova, Italy
[2] Marine Environment Research Centre (ENEA) – Santa Teresa, Pozzuolo di Lerici 19100, Italy

Received: 8 July 2013 – Accepted: 31 July 2013 – Published: 16 August 2013

Correspondence to: R. Bozzano (roberto.bozzano@cnr.it)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Three years of 300 kHz ADCP data collected in the central Ligurian Sea are analyzed to investigate the variability of the zooplankton biomass and the Diel Vertical Migrations (DVM) in the upper thermocline. After a pre-processing aimed at avoiding the slant range attenuation, hourly volume backscattering strength time series are obtained. Despite the lack of concurrent net samples collection, different migration patterns are identified and their temporal variability examined by means of time-frequency analysis. The effect of changes in the environmental condition is also investigated. Highest zooplankton biomasses are observed in April–May just after the peak of surface primary production in March–April. The main migration pattern points to a "nocturnal" migration with zooplankton organisms occurring deeper in the water column during the day and shallower at night. Also twilight migration is highlighted during this study. The largest migrations are recorded in November-December, corresponding to lowest backscattering strength values and are likely attributable to larger and more active organisms (i.e. euphausiids and mesopelagic fish). The results suggest further applications of the historical ADCP time series available.

1 Introduction

Acoustic Doppler Current Profiler (ADCP) is a widely used instrument to monitor the marine currents. Time series of these measurements span from a few days up to several years and are available for many coastal and open ocean sites. However, ADCP data may be usefully employed also to measure biological variables as pointed out by Flagg and Smith (1989) and Plueddemann (1989) at the end of 1980s, who showed that the acoustic backscatter signal was correlated with the zooplankton biomass. Since then, several biological investigations have been carried out by using ADCP observations (Rippeth and Simpson, 1998; Pinot and Jansá, 2001; Jiang et al., 2007; Ashjian et al., 2002, 1994; van Haren, 2007). Unfortunately, ADCP data are more qualitative than quantitative because the conversion from backscatter intensity to equivalent zooplankton biomass, usually obtained by direct comparison against coincident data from net samples, is somewhat problematic and the resulting relationship provides only rough estimates (Pinot and Jansá, 2001; Ashjian et al., 2002; Fielding et al., 2004). Nevertheless, the instrument, ensuring long-term autonomous monitoring, offers the opportunity to study the zooplankton distribution and its variability on many different temporal and spatial scales. Thus, its data supply important information required in marine ecology researches that cannot be satisfactorily obtained by using the classical observational methodology based on discrete net sampling.

Furthermore, ADCP data may help in reconstructing the diel vertical migration (DVM) of the zooplankton which is probably the biggest animal migration, in terms of biomass, on the planet (Hays, 2003). Since zooplankton represents the trophic link between primary producers (i.e. phytoplankton in the photic zone) and the higher trophic levels up to top-predators, the comprehension of their migratory patterns and biomass distribution is of crucial importance in understanding the pelagic ecosystem functioning.

In this context, the paper analyses the echo intensity and the vertical velocity data obtained from an ADCP moored in the open Ligurian Sea from September 2003 to February 2006 in terms of variations in the zooplankton biomass and DVM. These patterns are discussed taking into account the results achieved by several different previous studies carried out in one of the most dynamically active regions in the Mediterranean.

Although the experiment did not include specific biological measurements, the aim of this work is to highlight the usefulness of long term ADCP data series to enhance current knowledge on zooplankton, especially their migratory patterns.

The paper is organized in the following parts: Sect. 2 describes the investigated area, the data and the methodologies used in the study. The analysis of the zooplankton behavior and its variability with particular attention to the characteristic patterns of the DVM and the influence of some environmental variables is given in the Sect. 3. The results are discussed in the Sect. 4.

2 Materials and methods

2.1 Main features of the investigated area

The Ligurian Sea is a 3000 m deep basin, surrounded in the northern part by the Alps and limited by Corsica to the south. These topographic constraints and the thermal contrast between land and sea give rise to specific local effects that influence the general circulation of both atmosphere and ocean causing a strong variability in the upper ocean. The general circulation of the Ligurian Basin is characterized by a permanent basin-wide cyclonic circulation involving both the surface Modified Atlantic Water (MAW) and the lower Levantine Intermediate Water (LIW) (Crepon et al., 1982; Millot, 1999); it also shows important seasonal variability (Astraldi and Gasparini, 1992). The currents are generally weaker in summer than during winter and the contribution from the Tyrrhenian Sea is strongly reduced in summer. Significant inter-annual variability is observed (Vignudelli et al., 2000; Birol et al., 2010) as well as an intense mesoscale activity with marked seasonal variations (Taupier-Letage and Millot, 1986; Sammari et al., 1995).

Furthermore, due to the interplay of these particular climatic, oceanographic and physiographic factors, the area is highly productive and hosts a rich and complex ecosystem. This is also sustained by vertical mixing and coastal upwelling, generated by the prevailing north-westerly wind, which pumps deep nutrients and other organic substances contributed by rivers into the euphotic zone where they fertilize growing phytoplankton populations. Hence, the area attracts several cetacean species and is part of the "Cetacean Sanctuary" protected area, established to preserve the richness and variety of cetaceans living here with more than eight species including the fin whale *Balaenoptera physalus*.

All these issues make the Ligurian Basin a meaningful research site both for physicists and for biologists.

Several previous studies were conducted in the Ligurian Sea to determine the composition and biomass distribution of zooplankton communities (Licandro, 2000; Licandro and Icardi, 2009; Tarling et al., 2001; Andersen and Sardou, 1992; Sardou and Andersen, 1996). Although a comprehensive study which analyses the zooplankton composition at a seasonal scale in the whole Ligurian Basin is lacking, a rough reconstruction of species composition and dominance throughout a year can be done.

The mesozooplankton is mostly dominated by copepods (64 % of the total number of taxa), especially *Clausocalanus* spp., *Paracalanus* spp. and *Oithona* spp. (McGehee et al., 2004; Licandro, 2000). As a general pattern in the entire Mediterranean Sea, the bulk of the copepod population is concentrated in the epipelagic layer above 100 m depth with abundances decreasing sharply below 100 m (Mazzocchi et al., 2007; di Carlo et al., 1984; Weikert and Trinkaus, 1990; Brugnano et al., 2011).

Seasonal variations are observed in the composition of the zooplankton population with the dominance of different species throughout the year such as *Clausocalanus* spp. and *Fritillaria* spp. in winter, *Oithona helgolandica* and *Temora stylifera* in autumn (Licandro, 2000). In addition, due to the particular hydrographic conditions of the area, three main assemblages may be defined: one linked to the divergence zone of the basin, one associated to the periphery of the divergence and the latter with the eastern continental shelf (Licandro and Icardi, 2009). Each of them is identified by different biomass values, being least in the divergence zone (0.8–1.4 $\mathrm{mg\,m^{-3}}$), greater at the periphery of the divergence, and at its maximum in shallower waters on the eastern continental shelf (1.7–4.2 $\mathrm{mg\,m^{-3}}$), close to the study area, (Licandro and Icardi, 2009).

Among the macrozooplankton/micronekton, Tarling et al. (2001) report a dominance of euphausiids (mainly *Meganyctiphanes norvegica* and *Nematoscelis megalops*) and pteropods (almost exclusively *Cavolinia inflexa*) in September, while mostly *Nematoscelis megalops* is found in the Ligurian central zone in May (Andersen and Sardou, 1992). A further study by Sardou and Andersen (1996) shows that *M. norvegica* on the coastal side of the Ligurian front has peaks of abundance in February and again in August, as also confirmed by McGehee et al. (2004).

Overall, zooplankton dynamic is characterized in the Mediterranean by late winter and summer blooms which are ubiquitous in the different basins and are preceded by phytoplanktonic blooms related to environmental factors including stratification (Furnestin, 1960; Margalef, 1985). In the North-Western Mediterranean the late winter zooplankton bloom is generally delayed to spring (April–May) since the peak of surface primary production is generally recorded in February–March (Andersen, 2001a; Fanelli et al., 2009).

2.2 Environmental conditions during the period 2003–2006

The study was carried out in three periods related to the recovery and the re-positioning at sea of the mooring. Table 1 summarizes the instrumental setup of each deployment. Some unusual marine conditions occurred during each of the three periods. Particularly, the first one took place at the end of summer 2003, which was among the hottest of the last century. The anomalous warming affected the whole of Europe and, above all, the Central Mediterranean and was characterized by persistent calm weather conditions from May to the end of September 2003 (Sparnocchia et al., 2006). Several mass-mortality episodes were observed along Mediterranean coasts (Garrabou et al., 2009), as the strong vertical stratification prevented vertical mixing, thus reducing the oxygen contribution from both the atmosphere and the deeper layers and allowing intense warming of the surface waters. Only at the end of October 2003, after several strong winds events due to the passage of lows, the upper layers were completely mixed and normal conditions were again established. The second experiment was carried out during the severe winter 2004–2005 when very intense events of deep water formation took place in the North Western Mediterranean Sea despite significant warming and salinification of the entire water column which occurred in those years (Schroeder et al., 2008; Font and Emelianov, 2007). The third experiment was characterized by an anomalous long period of very weak currents lasting from April 2005 to February 2006. Indeed the recorded values did not exceed 30 $\mathrm{cm\,s^{-1}}$ till November when they increased during the passage of the only low system of the overall period and reached the maximum in the first days of January 2006. Moreover winter 2005–2006 showed an abrupt change of the water masses characteristics linked to deep water convection which occurred at the beginning of 2006 (Smith et al., 2008). Even current direction showed a very uncommon pattern with several episodes of eastward currents.

This significant inter-annual variability in the circulation was also evident in the horizontal currents measured by the ADCP used here (Fig. 1). The analysis was performed on the data collected from October to February, since this period was available for all three deployments.

During 2003–2004 currents were mainly direct towards North-Northwest and very few events of weak southward currents were recorded. On average, the mean hourly velocities were greater than 15 $\mathrm{cm\,s^{-1}}$, sometimes with peaks in the surface layers exceeding 60 $\mathrm{cm\,s^{-1}}$. On the contrary, during 2005–2006, the average of the mean hourly velocity was less than 10 $\mathrm{cm\,s^{-1}}$ at all depths and the maximum values never rose above 45 $\mathrm{cm\,s^{-1}}$. The prevailing current was to the West and occurrences of southward currents increased.

The anomalous behavior of the currents in the last period, both in velocity and direction, may be associated to the persistence over the Ligurian Sea of an high pressure system inducing an extraordinary long period of calm wind condition. Furthermore, the presence of saltier, warmer and shallower-than-normal intermediate water in the Ligurian Basin (compared with previous years) was responsible for dense water formation in 2006 and the unusual mixed layer depth of 2000 m in a basin where it is commonly a few hundred metres (Martín et al., 2010).

2.3 Experimental setup

The upward-looking RDI Sentinel 300 kHz ADCP was operating in the Central Ligurian Sea (43°47.77′ N; 9°02.85′ E) from 13 September 2003 to 22 February 2006 to investigate the upper layer dynamics in the area (Picco et al., 2010).

During this period, the mooring was recovered for maintenance and redeployed twice. Each time, according to the specific experimental design, the configuration of both mooring line and ADCP changed. The whole observation period was divided into three different phases (Table 1).

The vertical displacement of the mooring was checked using pressure measurements from a CTD device installed close to the ADCP and using the distance of the ADCP to water surface computed following Visbeck and Fischer (1995).

The mooring in all three periods showed good stability, indeed pitch and roll data never exceeded 2.5°, well below the 9° defined by the manufacturer as the limit for tilt compensation. Pitch and roll data showed a standard deviation less than than 1° for all three periods, satisfying the requirements for good velocities data (RD Instruments, 2003). All observations were quality checked; data were considered valid only if characterized by at least three beam solutions, if were satisfying the constraints of maximum range established by Gordon (1996) and for which the threshold of error velocity was not exceeded.

In all three periods the percentage of data rejected was less than 0.1 %. The final overall ADCP dataset consists of 11 063 hourly data and 14 934 samples with a sampling time of 30 min (Table 1).

Several supplementary data were used. Particularly, the sunrise/sunset times at the mooring location were computed by using the air–sea toolbox developed at Woods Hole Science Center (http://woodshole.er.usgs.gov/operations/sea-mat/air_sea-html/index.html), while surface wind data on the mooring site were obtained from the ERA-Interim (Dee et al., 2011) data base products from the European Centre for Medium-Range Weather Forecasts (ECMWF).

In addition, values of net primary production (NPP) obtained from the Vertically Generalized Production Model based on MODIS and SeaWIFS measurements (http://www.science.oregonstate.edu/ocean.productivity) were used as proxies of surface primary production in the area (Behrenfeld and Falkowski, 1997). Considering the normal delay of about one month between peaks of surface production and the increase in zooplankton biomass (Truscott and Brindley, 1994) values of NPP may help to interpret the ADCP profiles observed.

2.4 Volume backscattering strength computation

The measure of the echo intensity scattered by the ocean is usually given in terms of volume backscattering strength (Sv hereafter) dB re $(4\pi m)^{-1}$. Following Deines (1999), Sv is computed for each depth cell along each of the four beams through the Eq. (1):

$$Sv = C + 10\log_{10}((T_x + 273.16)R^2) - L_{\mathrm{DBM}} - P_{\mathrm{DBM}} + 2\alpha R + K_{\mathrm{c}}(E - E_{\mathrm{r}}) \quad (1)$$

where C (−143.5 dB) is the instrumental constant of RDI profilers for Workhorse Sentinel ADCP 300 kHz. T_x is the ADCP internal temperature in °C. L_{DBM} is the $10\log_{10}$ of the transmit pulse length in m (8.21 m for all three deployments). P_{DBM} is the $10\log_{10}$ of the transmit power in watt, defined by RDI for the ADCP model here used as 14 dBW. E is the echo intensity provided by the ADCP, E_{r} (40 counts) is the echo reference value when there is no signal and it is specifically determined for each instrument. K_{c} is the factor for converting to dB unit the raw echo data provided by the ADCP and it is defined through Eq. (2) as shown in the RD Instruments (2003):

$$K_{\mathrm{c}} = \frac{127.3}{T_x + 273} \quad (2)$$

α is the sound absorption coefficient for the seawater that is variable with depth and it is computed according to Ainslie formula (Ainslie, 1998) formula, a simple expression which takes into account the contribution of boric acid, magnesium sulfate and pure water and depends on temperature and salinity. These last two parameters are obtained from the climatological MED6 data base, a gridded monthly mean of in situ measurements of temperature and salinity for the whole Mediterranean and the near North Atlantic area at 1/4° resolution (Brankart and Pinardi, 2001). Data from the MED6 data base are selected in a 0.25°, square centered on 9.375° E; 43.75° N, the grid point closest to the mooring.

R is the slant range to the scattering layers being measured along the beam in metres expressed by Eq. (3):

$$R = \frac{B + \left(\frac{L+D}{2}\right) + [(n-1)D] + \frac{D}{4}}{\cos\theta}\,\frac{C'}{C_1} \tag{3}$$

where B is the blank in metres (1.76 m for all deployments), L is the transmit pulse length in metres, D is the depth cell length in metres (8 m for all deployments), n is the depth cell number of the scattering layer being measured, θ is the beam angle in degrees (20°). C_1 is the speed of sound in the water used by the ADCP and it is set to 1475.1 $\mathrm{m\,s^{-1}}$, while C' is the average sound speed from the transducer to the range cell that depends on the depth and is computed by means of Mackenzie formula (MacKenzie, 1981) using the same MED6 data previously extracted and interpolated at a vertical resolution of 1 m from 0 down to 100 m. To be used in Eq. (1), the slant range should not be less than $\pi R_0/4$, where R_0 is the Rayleigh distance defined by RDI for the Workhorse Sentinel 300 kHz ADCP as 0.98 m, and, according to Gordon (1996), the maximum range of acceptable data $R_{\max}$ should satisfy Eq. (4):

$$R_{\max} = H\cos\theta \tag{4}$$

where H is the distance of the instrument to the surface. In all three deployments both requirements were satisfied. The backscatter strength value Sv was obtained by averaging the results of Eq. (1) applied to the four available beams. The averaged Sv profiles for the three deployments at different depths are shown in Fig. 2. These values can be influenced by a low signal to noise ratio as pointed out by Gostiaux and van Haren (2010) who suggest to modify Eq. (1) as:

$$Sv = 20\log_{10}(R) + 2\alpha R - A + 10\log_{10}\left(10^{K_c E/10} - 10^{K_c E_r/10}\right) \tag{5}$$

and to introduce the ADCP transmit lag L_a in Eq. (3), thus obtaining Eq. (6):

$$R = \frac{B + \left(\frac{L+D+L_a}{2}\right) + [(n-1)D] + \frac{D}{4}}{\cos\theta} \tag{6}$$

In order to determine the constant A, a best linear fit between the Sv values obtained by Gostiaux and van Haren equation and the Sv values calculated by the Deines formula is performed using only the bins that satisfy the test $K_c(E - E_r) > 10$. In 2003–2004 data set, the signal to noise ratio is very high for almost all acquired data, so that the improvement of the Gastiaux and van Haren equation is limited to a quite constant little shift for all layers. On the contrary, in the 2004–2005 data, the differences between the backscattering strength values computed by the two methods increase with the growing of the slant range. These differences become more marked for the data acquired in the third deployment and disagreement is also found for the first two bins.

Furthermore, the closest bin to the transducer is characterized by a very weak signal and consequently the ADCP profile shows a high gradient on the second bin: this behavior is due to the transient time needed by the instrument to transmit and receive the signal, thus during this gap of time the acquired data can be erroneous (Lane et al., 1999).

Taking into account the previous issues, the used Sv values have been computed using (5) and discarding the bin closest to the transducer, as well as the one closest to the sea surface since it may be strongly affected by the atmosphere (Schott, 1989).

3 Results and discussion

3.1 Seasonal variability

The monthly mean backscattering strength values computed for each time series at the common depth of about 40 m are shown in Fig. 3. Although none of the time series covers an entire year and not all months are complete, the three distributions show similar seasonal behavior, with an increase in spring and lower values during the fall months. A relative maximum is also detected in January–February, while an abrupt drop, with very low values, is recorded in July 2005.

The seasonal net primary production values show a pronounced inter-annual variability (Fig. 4). In 2003 the mean annual NPP cycle is characterized by two peaks, the major one in April (707 $\mathrm{mg\,C\,m^{-2}\,day^{-1}}$) and the other in November (481 $\mathrm{mg\,C\,m^{-2}\,day^{-1}}$). In 2004 there is a unique peak of NPP from March to May (mean NPP = $706 \pm 70\,\mathrm{mg\,C\,m^{-2}\,day^{-1}}$), while in 2005 an extraordinary high NPP peak is recorded from April (1221 $\mathrm{mg\,C\,m^{-2}\,day^{-1}}$) to May (1070 $\mathrm{mg\,C\,m^{-2}\,day^{-1}}$), but high NPP values persist until August (on average $547 \pm 42\,\mathrm{mg\,C\,m^{-2}\,day^{-1}}$).

The pattern of backscattering strength values is consistent with NPP trends with the expected delay of about 1 month between peak of surface primary production and the response by the zooplankton community. Indeed, the peak of zooplankton biomass is recorded in April–May (Fig. 3) after the peak of NPP in March–April (Fig. 4). The unusual high value found in September 2005 (Fig. 3, bottom) is fairly well explained by the persistent high surface production that take place from May to August 2005 (Fig. 4).

The observed time series is also in agreement with the distribution of monthly mean Continuous Plankton Recorder (CPR) data collected in the North-West Mediterranean Sea in the period 1977–1999 (Licandro and Icardi, 2009) and this time series is substantially uniform down the water column, at least to 30 m depth, while a greater variability is noted below this depth and between the three time series.

3.2 Daily mean cycle

The first experiment starts at the end of the anomalous warm summer 2003 and the measures are limited to the upper 50 m of the sea. From the beginning of the observational period in September 2003 to the first half of October, the mean daily backscatter strength values are high, particularly in the layers above 30 m depth (Fig. 5). Starting from mid October until the first days of December 2003, with the exception in early November, they undergo to a significant decrease and slightly high values are recorded only sporadically below 30 m. From mid December 2003, the signal begins to grow and the whole observed water column becomes substantially homogeneous. From mid April the measured values are again high even if only on a few occasions reaching those recorded in October. A weak reduction appears in the surface layer shortly before the recovery of the mooring at the end of May 2004.

The mooring configuration adopted in the second experiment allows investigation down to 80 m depth. The mean daily backscatter strength data collected above 35 m depth show a trend similar to the one of the previous period 2003–2004: starting from mid October 2004 the values decrease until December when they start to grow slowly again to reach, after a short period of attenuation in March 2005, the highest values in April. However, in the upper 30 m layers the *Sv* values remain high during the whole time and the homogenization of the examined water column occurs only sporadically below 25 m depth until January 2005, when strong signals begin to be registered even in the deepest layers. At the end of March, after a short period of decrease, which affects the water column up to almost the surface, the *Sv* values are large at all depths.

Summer data are available only for the third experiment in a long period of exceptionally calm conditions of both marine and atmospheric dynamics. From mid June to the end of August the recorded *Sv* values are very small, especially below 30 m depth. A significant reduction of total zooplankton biomass in the summer months also showed in the CPR data (Licandro and Icardi, 2009). However, except for a few events of short duration, the mean daily backscatter remains weak until mid February when a significant further drop is observed just before the end of the measurements.

Despite the significant inter-annual differences, a fairly constant characteristic in the distributions of the monthly mean hourly *Sv* data is the presence of a marked daily cycle, with low values during the daylight and high ones in the night (Fig. 6). In correspondence with the sudden changes in the *Sv* signal, negative peaks in the early morning and positive ones in the afternoon are found in the monthly distributions of the vertical velocity mean hourly values (Fig. 7).

A noteworthy agreement results between the time of sunrise and sunset at the mooring position and the time at which the lowest and highest daily values of both vertical velocity and *Sv* hourly changes occur, especially for the third period when the used sampling time is set at 30 min.

3.3 Diel vertical migration

Results mentioned above can be ascribed to the diel vertical migration performed by several species of the zooplankton population. This is a vertical movement, generally involving a 24 h cycle, the causes of which are not yet fully understood (Ringelberg, 2010). Three main patterns have been identified: “normal” or “nocturnal” DVM involves animals moving deeper in the water column during the day and shallower at night. A less common behavior exhibits a slow descent following arrival at the surface at dusk, and a subsequent second ascent to the surface towards the end of the night, prior to the dawn descent (“twilight migration”). Other species or live stages undergo “reverse migration”, where the zooplankton ascend at dawn and descend at dusk (Heywood, 1996; Jiang et al., 2007; Cisewski et al., 2010).

The backscatter strength shows significant differences both in time and with depth. To better investigate these patterns, two different datasets for each experiment are obtained separating the observations taken between sunrise and sunset (Fig. 8, on the left) from those collected between sunset and sunrise (Fig. 8, on the right).

During the first experiment, the measured data show a quite uniform vertical distribution of the backscattering strength. These values are for most of the examined period rather large during both day and night. Only in two periods, between October and December 2003 and for few days in January 2004, the diurnal values undergo a significant reduction denoting fewer scatter organisms during daylight. In the second and third experiments such small values are never observed above 30 m depth. In this upper layer the backscatter strength signal remains large with small differences between day and night. Below 40 m depth a strong reduction is often observed during daylight, while in the night the signal increases and has a tendency to homogenize the whole observed water column.

3.4 Spectral analysis

The spectral analysis performed on the three time series does not differ significantly among samples. It is characterized by a dominant 24 h peak and a series of minor peaks on the higher harmonics. It confirms the predominance of a signal with a 24 h cycle corresponding to the so called “normal” or “nocturnal” pattern (Fig. 9). The secondary 12 h peak may be attributable to a different DVM pattern, the so-called twilight migration (Cushing, 1951).This is sometimes distinguished in the hourly *Sv* values, especially during the third experiment that has 30 min temporal resolution (Fig. 10).Twilight migrations were found in more than 80 % of records of Western North Atlantic zooplankton DVM (Ashjian et al., 1994). The observed behavioral patterns have different interpretations, with hunger-satiation and escapes from predators (i.e. krill) as the most plausible causes (Tarling et al., 1999).

Time-frequency analysis provides evidence for the temporal evolution of the amplitude of each signal and allows to identify the periods when a signal characterizing a specific DVM pattern – in this case 24 h and 12 h – is prevailing. The spectrograms are obtained using a 240 h sliding window with 216 h overlap between each sample. For all three periods, the time evolution of the amplitude of the 24 h and 12 h harmonics at different depths are given in Fig. 11.

The three distributions show that both 12 h and 24 h cycles are particularly intense between November and December when the backscattering strength values are least. Furthermore, during the first experiment the maximum of the spectrum for the 24 h harmonic is obtained for the surface layer, while it is found at 40 m depth for the 12 h harmonic. On the contrary, during the other two experiments, the spectrum for both harmonics is weak at the surface. The 24 h harmonic time series shows the maximum amplitude at 40 m depth, and the 12 h at the deepest layers.

These results may suggest the presence of different type of zooplankton organisms, some of which migrate according to their own specific DVM pattern, while others are stationary, as observed in other areas like in the Irish Sea where generally more than

60 % of the zooplankton community does not perform significant DVM (Irigoien et al., 2004).

Particularly, the widest migrations appear when the backscatter is weak. These migrations may be ascribed to some large and more active organisms, likely macrozooplankton and micronekton (i.e. euphausiids, small mesopelagic fish) which are quite abundant in late autumn in other areas of the North Western Mediterranean (McGehee et al., 2004; Olivar et al., 2012).

3.5 Vertical velocities and changes in the zooplankton population

Data obtained by ADCP are considered to be an average of a backscattering field consisting of both migrating and stationary organisms (Plueddemann, 1989). Depending on the prevalence of one or another organism, the DVM signal may be more or less detectable by ADCP measurements. Each migrating species has its own behavior that may change during the different stages of life and due to environmental conditions. Furthermore, although the ADCP measurements do not give the true value of the zooplankton vertical speed but, generally, a lesser one (Plueddemann, 1989; Tarling et al., 2001), the analysis of the recorded mean hourly vertical velocity may help to investigate if part of the observed variability could be ascribed to a change of the proportion between the different genotypes making up the observed zooplankton population.

Almost all of the vertical velocity data have values close to zero. Values greater than $\pm 0.5\,\mathrm{cm\,s^{-1}}$ are recorded mainly in conjunction with changes of Sv or during strong wind events.

As a result, the analysis is carried out on the time series of the maximum and minimum daily values (Fig. 12). The distributions of maximum and minimum mean hourly vertical velocity show that the values tend to increase from the first to the third experiment and going from the surface to the deepest layers. In fact, during the first deployment more than 94 % of the values are between $\pm 1.5\,\mathrm{cm\,s^{-1}}$, of which 40 % fall in the range $\pm 0.5\,\mathrm{cm\,s^{-1}}$. During the second deployment, the percentage in the range $\pm 1.5\,\mathrm{cm\,s^{-1}}$ is still greater than 90 %, but far fewer values are between $\pm 0.5\,\mathrm{cm\,s^{-1}}$ and the decrease is even more evident in the deepest layer where they are less than 10 %. During the third deployment the recorded values are larger at all depths and fewer than 10 % are in the interval ±0.5 $\mathrm{cm\,s^{-1}}$.

Although during the first experiment the extreme values of the vertical velocity are small, the analysis of the daily data shows that, under strong wind conditions lasting a few days, peaks of up to 5 $\mathrm{cm\,s^{-1}}$ and more are recorded, mainly in the surface layer whilst they decrease with depth. These large values are never reached in the other two periods despite the occurrence of several episodes with even stronger wind. Furthermore, the first period is also characterized by a different distribution of the vertical velocities. This does not show any particular seasonal pattern, but rather single episodes whose amplitude is less in spring. On the contrary, a weak seasonal trend may be detected for the data collected during the second and third periods. Particularly, the extreme values of the vertical velocity increase from the late summer to November when they start again to decrease reaching minimum values in January. During 2005–2006, an increase and subsequently decrease is also observed between the middle of June and the end of August.

4 Conclusions

Three years of acoustic backscatter and vertical velocities data collected by a 300 kHz ADCP in the Central Ligurian Sea are analyzed to investigate the zooplankton dynamics. Even based on only one frequency and without net samples, the analysis of backscatter variability at different time scales allows to identify different zooplankton migration patterns and, from these, to infer about its presence and composition in the area.

At seasonal scale, the biomass follows the NPP signal with a delay of about one month having higher values in April and May and a secondary maximum in January or February; lower values are generally observed in autumn.

The prevailing vertical migration pattern is the 24 h cycle performed by the zooplankton swimming upward at the sunset and downward at the sunrise. A second pattern having a 12 h cycle is also identified, the twilight migration, in particular in the measurements with 30 min temporal resolution.

Furthermore, the analysis of both *Sv* and vertical velocity data suggests that changes in composition of zooplankton population may occur during the three years of continuous monitoring.

Although no biological sampling was performed during the experiments, the results of several studies made in adjacent areas (Licandro, 2000) and the zooplankton composition there reported can help in interpreting the findings of this ADCP data analysis. Among the mesozooplanktonic species which are abundantly found in those studies such as *Clausocalanus* spp., *Paracalanus* spp. and *Oithona* spp. (McGehee et al., 2004; Licandro, 2000), no one species shows a strong diel vertical migration (Andersen, 2001b). Indeed, according to Brugnano et al. (2011), in the area only species of the *Scolecithrellidae* family show significant DVM, confirming previous information about the presence of few strong migrants in the Mediterranean Sea. Thus, it may be supposed that the species mainly responsible for the strong *Sv* signal found in some periods of this study, at times of small biomass, are ascribable to the macroplanktonic/micronektonic component. Particularly, the area is dominated by the euphausiid *Meganyctiphanes norvegica* (Tarling et al., 2001; Andersen, 2001a) which attains its maximum abundance values in August–September. This species is known to perform wide vertical migration (Kaartvedt, 2010) and it could be responsible of the maximum amplitude found in ADCP data recorded in September 2006.

Furthermore, other previous investigations (Boucher et al., 1987; Licandro, 2000; McGehee et al., 2004; de Puelles and Molinero, 2008; Raybaud et al., 2008; Licandro and Icardi, 2009) point out that the Ligurian Sea is characterized by different zooplankton populations whose distribution is related to the main hydrological features of this basin. The importance of Mediterranean circulation dynamics in the determination of different zooplankton associations was also found in the Gulf of Trieste (Cataletto, 1995) and in the Gulf of Naples (Carrada et al., 1980).

Water masses and marine circulation of the whole Mediterranean Sea, and particularly of the Ligurian Basin, underwent major changes over the three years of the study. The contemporaneous measurements of sea currents show a significant modification in the study area with an anticlockwise rotation from North to West and a decrease of intensity (Fig. 1). This may lead to the dominance of different zooplankton associations, related to changes in current intensity and direction, as observed by Licandro (2000) in a long-term study in the Gulf of Tigullio, an area adjacent to the ADCP mooring position.

At the present, many long time series of ADCP data have been collected to estimate horizontal and vertical oceanic currents. The results of this study suggest that their re-examination in terms of backscatter signals can contribute to deepen the zooplankton knowledge even in absence of corresponding biological observations.

Acknowledgement. The work has been partially funded by the Flagship Project RITMARE – The Italian Research for the Sea – coordinated by the National Research Council of Italy and funded by the Italian Ministry of Education, University and Research within the National Research Program 2011–2013.

References

Ainslie, M. A.: A simplified formula for viscous and chemical absorption in sea water, J. Acoust. Soc. Am., 103, 1671–1672, 1998. 1375

Andersen, V.: Zooplankton community during the transition from spring bloom to oligotrophy in the open NW Mediterranean and effects of wind events. 1. Abundance and specific composition, J. Plankton Res., 23, 227–242, 2001a. 1372, 1384

Andersen, V.: Zooplankton community during the transition from spring bloom to oligotrophy in the open NW Mediterranean and effects of wind events. 2. Vertical distributions and migrations, J. Plankton Res., 23, 243–261, 2001b. 1384

Andersen, V. and Sardou, J.: The diel migrations and vertical distributions of zooplankton and micronekton in the Northwestern Mediterranean Sea. 1. Euphausiids, mysids, decapods and fishes, J. Plankton Res., 14, 1129–1154, 1992. 1371

Ashjian, C. J., Smith, S. L., Flagg, C. N., Mariano, A. J., and Beherens, W. J.: The influence of a Gulf Stream meander on the distribution of zooplankton biomass in the Slope Water, the Gulf Stream, and the Sargasso Sea, described using a shipboard acoustic Doppler current profiler, Deep-Sea Res. Pt. I, 41, 23–50, 1994. 1368, 1381

Ashjian, C. J., Smith, S. L., Flagg, C. N., and Idrisi, N.: Distribution, annual cycle, and vertical migration of acoustically derived biomass in the Arabian Sea during 1994–1995, Deep-Sea Res. Pt II, 49, 2377–2402, 2002. 1368, 1369

Astraldi, M. and Gasparini, G. P.: The seasonal characteristics of the circulation in the north Mediterranean Basin and their relationship with the atmospheric-climatic conditions, J. Geophys. Res., 97, 9531–9540, 1992. 1370

Behrenfeld, M. J. and Falkowski, P. G.: Photosynthetic rates derived from satellite-based chlorophyll concentration, Limnol. Oceanogr., 42, 1–20, 1997. 1374

Birol, F., Cancet, M., and Estournel, C.: Aspects of the seasonal variability of the Northern Current (NW Mediterranean Sea) observed by altimetry, J. Marine Syst., 81, 297–311, 2010. 1370

Boucher, J., Ibanez, F., and Prieur, L.: Daily and seasonal variations in the spatial distribution of zooplankton populations in relation to the physical structure in the Ligurian Sea Front, J. Mar. Res., 45, 133–173, 1987. 1384

Brankart, J.-M. and Pinardi, N.: Abrupt cooling of the Mediterranean Levantine intermediate water at the beginning of the 1980s: observational evidence and model simulation, J. Phys. Oceanogr., 31, 2307–2320, 2001. 1375

Brugnano, C., DAdamo, R., Fabbrocini, A., Granata, A., and Zagami, G.: Zooplankton responses to hydrological and trophic variability in a Mediterranean coastal ecosystem (Lesina Lagoon, South Adriatic Sea), Chem. Ecol., 27, 461–480, 2011 1371, 1384

Carrada, G. C., Hopkins, T. S., Bonaduce, G., Ianora, A., Marino, D., Modigh, M., Ribera, D. M., and Scotto, C. B.: Variability in the hydrographic and biological features of the Gulf of Naples, Mar. Ecol., 1, 105–120, 1980. 1385

Cataletto, B.: Eleven years of time-series analysis on the net-zooplankton community in the Gulf of Trieste, Ices J. Mar. Sci., 52, 669–678, 1995. 1385

Cisewski, B., Strass, V. H., Rhein, M., and Krägefsky, S.: Seasonal variation of diel vertical migration of zooplankton from ADCP backscatter time series data in the Lazarev Sea, Antarctica, Deep-Sea Res. Pt. I, 57, 78–94, 2010. 1380

Crepon, M., Wald, L., and Monget, J. M.: Low-frequency waves in the Ligurian Sea during December 1977, J. Geophys. Res., 87, 595–601, 1982. 1370

Cushing, D. H.: The vertical migration of planktonic crustacea, Biol. Rev., 26, 158–192, 1951. 1381

de Puelles, M. L. F. and Molinero, J. C.: Decadal changes in hydrographic and ecological time-series in the Balearic Sea (western Mediterranean), identifying links between climate and zooplankton, Ices J. Mar. Sci., 65, 311–317, 2008. 1384

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. Roy. Meteor. Soc., 137, 553–597, 2011. 1374

Deines, K. L.: Backscatter estimation using Broadband acoustic Doppler current profilers, in: Working Conference on Current Measurement, 1999. 1375

di Carlo, B., Ianora, A., Fresi, E., and Hure, J.: Vertical zonation patterns for Mediterranean copepods from the surface to 3000 m at a fixed station in the Tyrrhenian Sea, J. Plankton Res., 6, 1031–1056, 1984. 1371

Fanelli, E., Cartes, J. E., Rumolo, P., and Sprovieri, M.: Food-web structure and trophodynamics of mesopelagic–suprabenthic bathyal macrofauna of the Algerian Basin based on stable isotopes of carbon and nitrogen, Deep-Sea Res. Pt. I, 56, 1504–1520, 2009. 1372

Fielding, S., Griffiths, G., and Roe, H. S. J.: The biological validation of ADCP acoustic backscatter through direct comparison with net samples and model predictions based on acoustic-scattering models, Ices J. Mar. Sci., 61, 184–200, 2004. 1369

Flagg, C. and Smith, S.: On the use of the acoustic Doppler current profiler to measure zooplankton abundance, Deep-Sea Res. Pt I, 36, 455–474, 1989. 1368

Font, J., Puig, P., Salat, J., Palanques, A., and Emelianov, M.: Sequence of hydrographic changes in NW Mediterranean deep water due to the exceptional winter of 2005, Sci. Mar., 71, 339–346, 2007. 1372

Furnestin, M. L.: Zooplancton du Golfe du Lion et de la côte orientale de Corse, Rev. Trav. Inst. Pêches Marit., 24, 153–252, 1960. 1372

Garrabou, J., Coma, R., Bensoussan, N., Bally, M., Chevaldonné, P., Cigliano, M., Diaz, D., Harmelin, J., Gambi, M., Kersting, D., Ledoux, J., Lejeusne, C., Linares, C., Marschal, C., Pérez, T., Ribes, M., Romano, J., Serrano, E., Teixido, N., Torrents, O., Zabala, M., Zuberer, F., and Cerrano, C.: Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave, Glob. Change Biol., 15, 1090–1103, 2009. 1372

Gordon, R.: Acoustic Doppler Current Profilers Principles of Operation: A Practical Primer, RD Instruments, 1996. 1374, 1376

Gostiaux, L. and van Haren, H.: Extracting Meaningful Information from Uncalibrated Backscattered Echo Intensity Data, J. Atmos. Ocean. Tech., 27, 943–949, 2010. 1376

Hays, G. C.: A review of the adaptive significance and ecosystem consequences of zooplankton diel vertical migrations, Hydrobiologia, 503, 163–170, 2003. 1369

Heywood, K. J.: Diel vertical migration of zooplankton in the Northeast Atlantic, J. Plankton Res., 18, 163–184, 1996. 1380

Irigoien, X., Conway, D., and Harris, R.: Flexible diel vertical migration behaviour of zooplankton in the Irish Sea, Mar. Ecol.-Prog. Ser., 267, 85–97, 2004. 1382

Jiang, S., Dickey, T. D., Steinberg, D. K., and Madin, L. P.: Temporal variability of zooplankton biomass from ADCP backscatter time series data at the Bermuda Testbed Mooring site, Deep-Sea Res. Pt. I, 54, 608–636, 2007. 1368, 1380

Kaartvedt, S.: Diel Vertical Migration Behaviour of the Northern Krill (Meganyctiphanes norvegica Sars), vol. 57, 2010. 1384

Lane, A., Knight, P. J., and Player, R. J.: Current measurement technology for near-shore waters, Coast. Eng., 37, 343–368, 1999. 1377

Licandro, P.: Changes of zooplankton communities in the Gulf of Tigullio (Ligurian Sea, Western Mediterranean) from 1985 to 1995, Influence of hydroclimatic factors, J. Plankton Res., 22, 2225–2253, 2000. 1370, 1371, 1384, 1385

Licandro, P. and Icardi, P.: Basin scale distribution of zooplankton in the Ligurian Sea (northwestern Mediterranean) in late autumn, Hydrobiologia, 617, 17–40, 2009. 1370, 1371, 1378, 1379, 1384

MacKenzie, K. V.: Nine-term equation for sound speed in the oceans, J. Acoust. Soc. Am., 70, 807–812, 1981. 1376

Margalef, R.: Environmental Control of the Mesoscale Distribution of Primary Producers and Its Bearing to Primary Production in the Western Mediterranean, Plenum Press, 1985. 1372

Martín, J., Miquel, J.-C., and Khripounoff, A.: Impact of open sea deep convection on sediment remobilization in the western Mediterranean, Geophys. Res. Lett., 37, 1–6, 2010. 1373

Mazzocchi, M. G., Christou, E. D., Capua, I. D., de Puelles, M. F., Fonda-Umani, S., Molinero, J. C., Nival, P., and Siokou-Frangou, I.: Temporal variability of Centropages typicus in the Mediterranean Sea over seasonal-to-decadal scales, Prog. Oceanogr., 72, 214–232, 2007. 1371

McGehee, D., Demer, D., and Warren, J.: Zooplankton in the Ligurian Sea: Part I. Characterization of their dispersion, relative abundance and environment during summer 1999, J. Plankton Res., 26, 1409–1418, 2004. 1371, 1382, 1384

Millot, C.: Circulation in the Western Mediterranean Sea, J. Marine Syst., 20, 423–442, 1999. 1370

Olivar, M., Bernal, A., Molí, B., Péna, M., Balbín, R., Castellón, A., Miquel, J., and Massutí, E.: Vertical distribution, diversity and assemblages of mesopelagic fishes in the western Mediterranean, Deep-Sea Res. Pt. I, 62, 53–69, 2012. 1382

Picco, P., Cappelletti, A., Sparnocchia, S., Schiano, M. E., Pensieri, S., and Bozzano, R.: Upper layer current variability in the Central Ligurian Sea, Ocean Sci., 6, 825–836, doi:10.5194/os-6-825-2010, 2010. 1373

Pinot, J. and Jansá, J.: Time variability of acoustic backscatter from zooplankton in the Ibiza Channel (western Mediterranean), Deep-Sea Res. Pt. I, 48, 1651–1670, 2001. 1368, 1369

Plueddemann, A.: Characterization of the patterns of diel migration using a Doppler sonar, Deep-Sea Res. Pt. I, 36, 509–530, 1989. 1368, 1382

Raybaud, V., Nival, P., Mousseau, L., Gubanova, A., Altukhov, D., Khvorov, S., Ibañez, F., and Andersen, V.: Short term changes in zooplankton community during the summer-autumn transition in the open NW Mediterranean Sea: species composition, abundance and diversity, Biogeosciences, 5, 1765–1782, doi:10.5194/bg-5-1765-2008, 2008. 1384

RD Instruments: WinRiver User's Guide, 2003. 1374, 1375

Ringelberg, J.: Diel Vertical Migration of Zooplankton in Lakes and Oceans: Causal Explanations and Adaptive Significances, Springer, the Netherlands, 2010. 1380

Rippeth, T. and Simpson, J.: Diurnal Signals in Vertical Motions on the Hebridean Shelf, 1998. 1368

Sammari, C., Millot, C., and Prieur, L.: Aspects of the seasonal and mesoscale variabilities of the Northern Current in the western Mediterranean Sea inferred from the PROLIG-2 and PROS-6 experiments, Deep-Sea Res. Pt. I, 42, 893–917, 1995. 1370

Sardou, J., E. M. and Andersen, V.: Seasonal abundance and vertical distributions of macroplankton and micronekton in the Northwestern Mediterranean Sea, Oceanol. Acta, 19, 645–656, 1996. 1371

Schott, F.: Measuring winds from underneath the ocean surface by upward looking acoustic Doppler current profilers, J. Geophys. Res.-Oceans, 94, 8313–8321, 1989. 1377

Schroeder, K., Ribotti, A., Borghini, M., Sorgente, R., Perilli, A., and Gasparini, G. P.: An extensive western Mediterranean deep water renewal between 2004 and 2006, Geophys. Res. Lett., 35, 2008. 1372

Smith, R. O., Bryden, H. L., and Stansfield, K.: Observations of new western Mediterranean deep water formation using Argo floats 2004–2006, Ocean Sci., 4, 133–149, doi:10.5194/os-4-133-2008, 2008. 1373

Sparnocchia, S., Schiano, M. E., Picco, P., Bozzano, R., and Cappelletti, A.: The anomalous warming of summer 2003 in the surface layer of the Central Ligurian Sea (Western Mediterranean), Ann. Geophys., 24, 443–452, doi:10.5194/angeo-24-443-2006, 2006. 1372

Tarling, G., Matthews, J., David, P., Guerin, O., and Buchholz, F.: The swarm dynamics of northern krill (Meganyctiphanes norvegica) and pteropods (Cavolinia inflexa) during vertical migration in the Ligurian Sea observed by an acoustic Doppler current profiler, Deep-Sea Res. Pt. I, 48, 1671–1686, 2001. 1371, 1382, 1384

Tarling, G. A., Buchholz, F., and Matthews, J.: The effect of lunar eclipse on the vertical migration behaviour of Meganyctiphanes norvegica (Crustacea: Euphausiacea) in the Ligurian Sea, J. Plankton Res., 21, 1475–1488, 1999. 1381

Taupier-Letage, I. and Millot, C.: General hydrodynamical features in the Ligurian Sea inferred from the DYOME experiment, Oceanol. Acta, 9, 119–131, 1986. 1370

Truscott, J. E. and Brindley, J.: Equilibria, Stability and Excitability in a General Class of Plankton Population Models, Philosophical Transactions: Physical Sciences and Engineering, 347, 703–718, 1994. 1374

van Haren, H.: Echo intensity data as a directional antenna for observing processes above sloping ocean bottoms, Ocean Dynam., 57, 135–149, 2007. 1368

Vignudelli, S., Cipollini, P., Astraldi, M., Gasparini, G. P., and Manzella, G.: Integrated use of altimeter and in situ data for understanding the water exchanges between the Tyrrhenian and Ligurian Seas, J. Geophys. Res.-Oceans, 105, 19649–19663, 2000. 1370

Visbeck, M. and Fischer, J.: Sea Surface Conditions Remotely Sensed by Upward-Looking ADCPs, J. Atmos. Ocean. Tech., 12, 141–149, 1995. 1374

Weikert, H. and Trinkaus, S.: Vertical mesozooplankton abundance and distribution in the deep Eastern Mediterranean Sea SE of Crete, J. Plankton Res., 12, 601–628, 1990. 1371

Table 1. Experimental configuration of the ADCP during the three deployments from September 2003 to February 2006.

Period	No. of samples	Sample frequency	Depth	Bin size
13 Sep 2003–24 May 2004	6120	1 h	58 m	8 m
23 Sep 2004–15 Apr 2005	4943	1 h	100 m	8 m
19 Apr 2005–22 Feb 2006	14 934	30 min	80 m	8 m

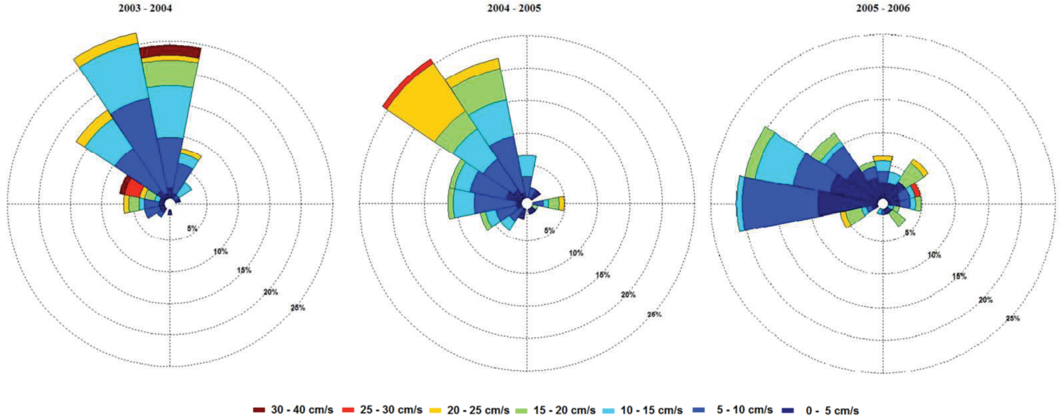

Fig. 1. Distribution of the horizontal currents recorded at 40 m depth from October to February during the three deployments.

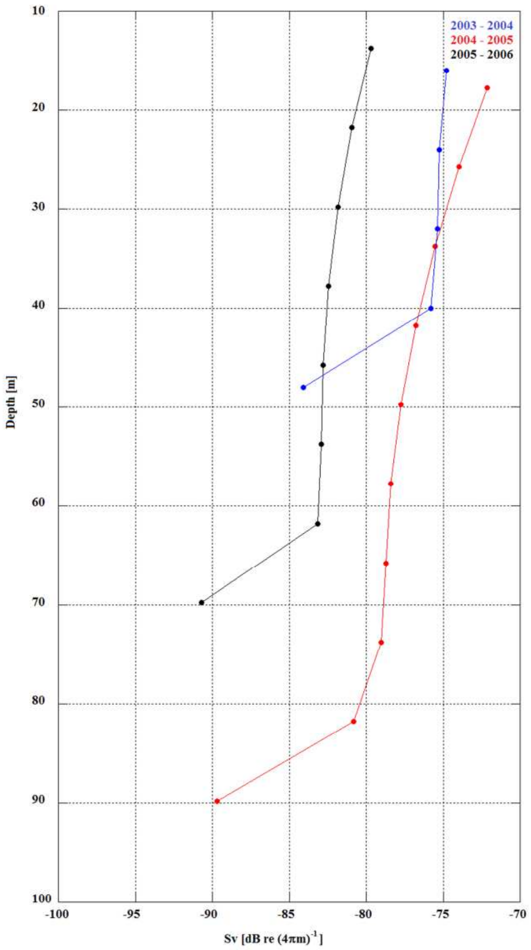

Fig. 2. Average backscatter strength profiles for the three deployments.

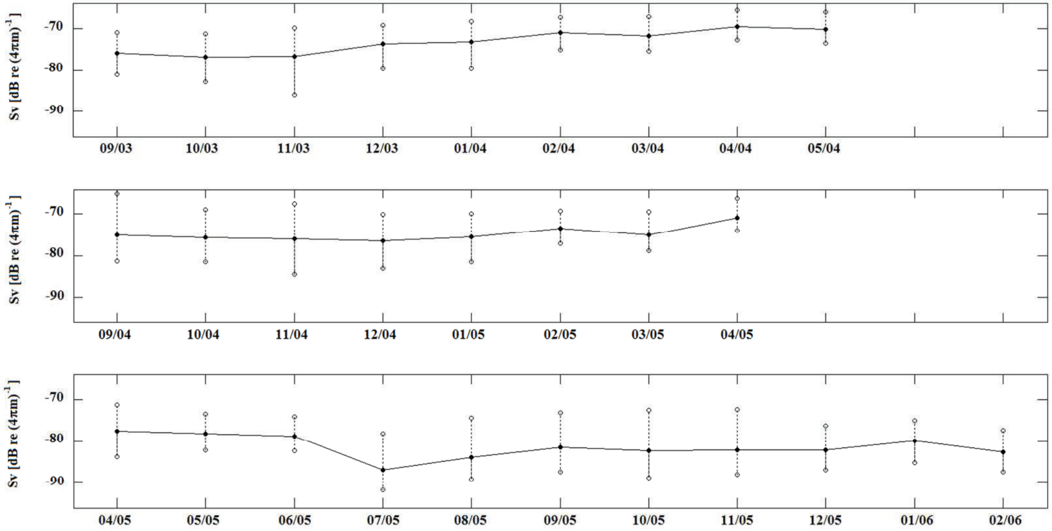

Fig. 3. Monthly mean, maximum and minimum values of backscatter strength at about 40 m depth during the three deployments.

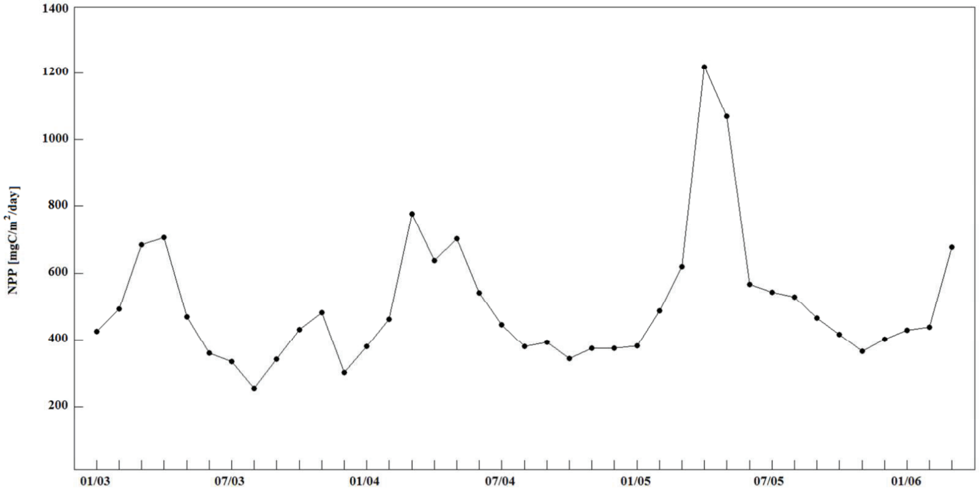

Fig. 4. Monthly averaged net primary production values recorded in the study area during the sampling period.

OSD
10, 1367–1404, 2013

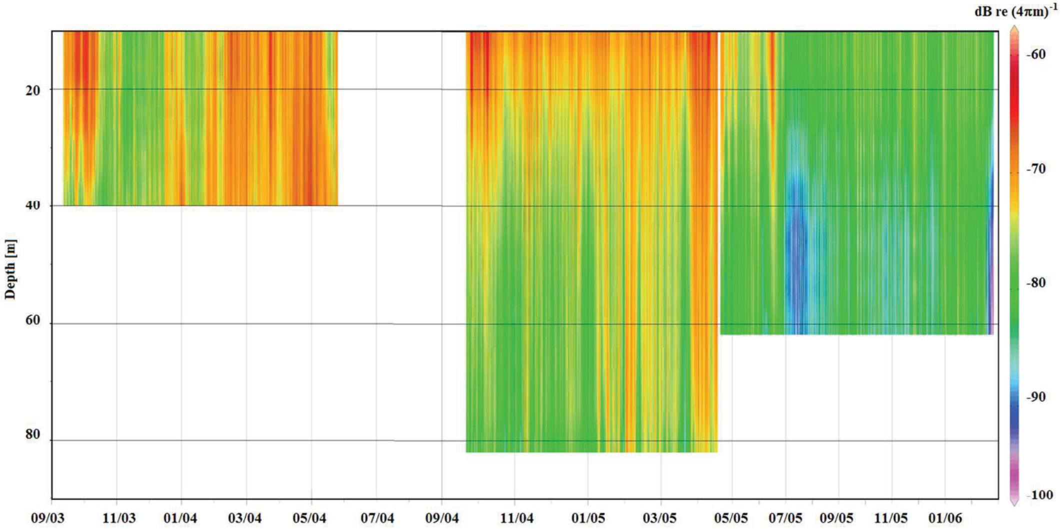

Fig. 5. Time series of daily mean backscatter strength data recorded during the three deployments.

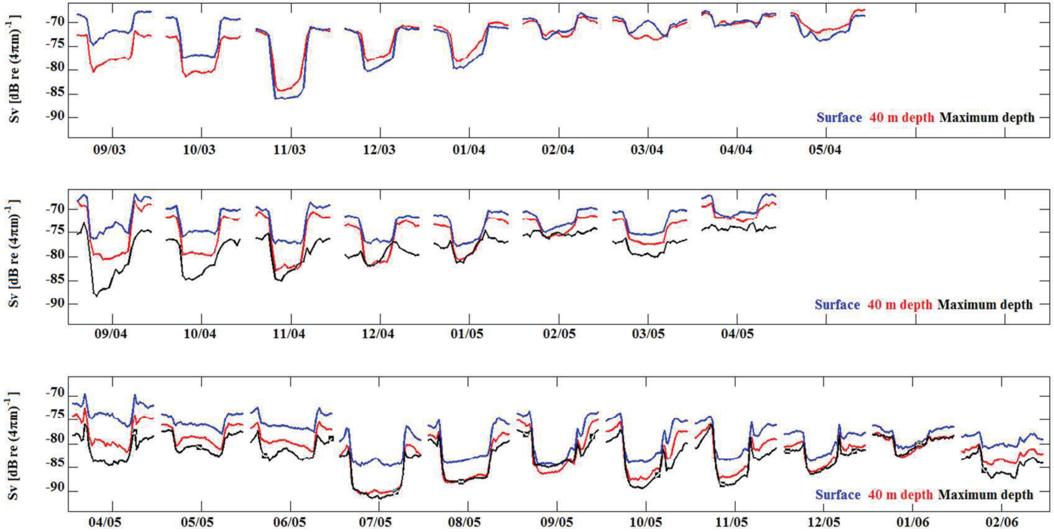

Fig. 6. Monthly mean daily cycle backscatter strength values at different depths.

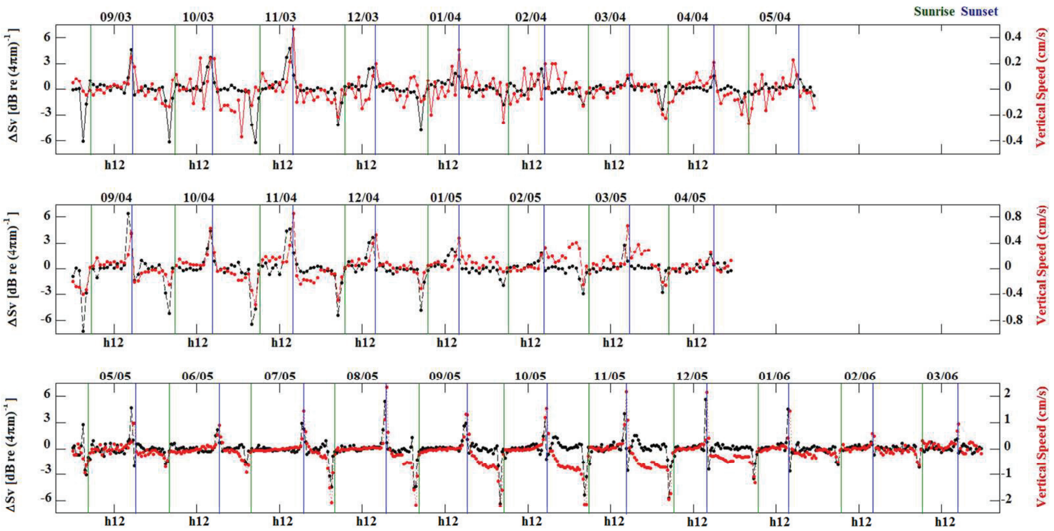

Fig. 7. Monthly mean daily cycle of temporal derivative of backscatter strength and vertical speed at about 40 m depth for the three deployments. Vertical lines correspond to the hour of sunrise and sunset of each month.

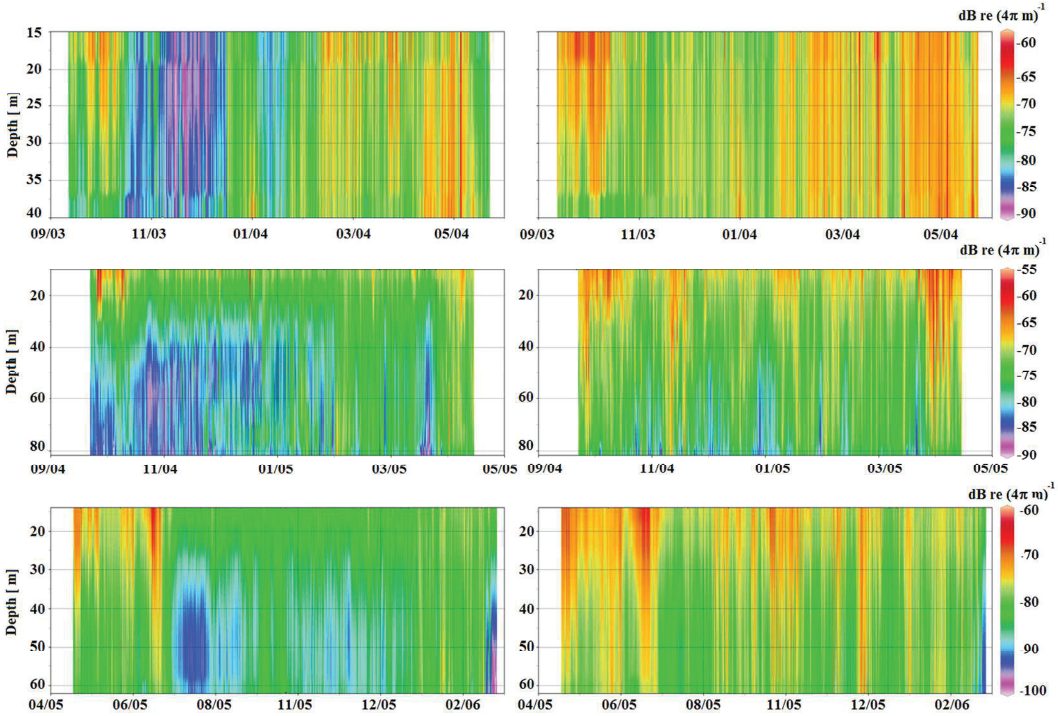

Fig. 8. Time series of backscatter strength profile for data collected between sunrise and sunset (on the left) and between sunset and sunrise (on the right) in the three deployments.

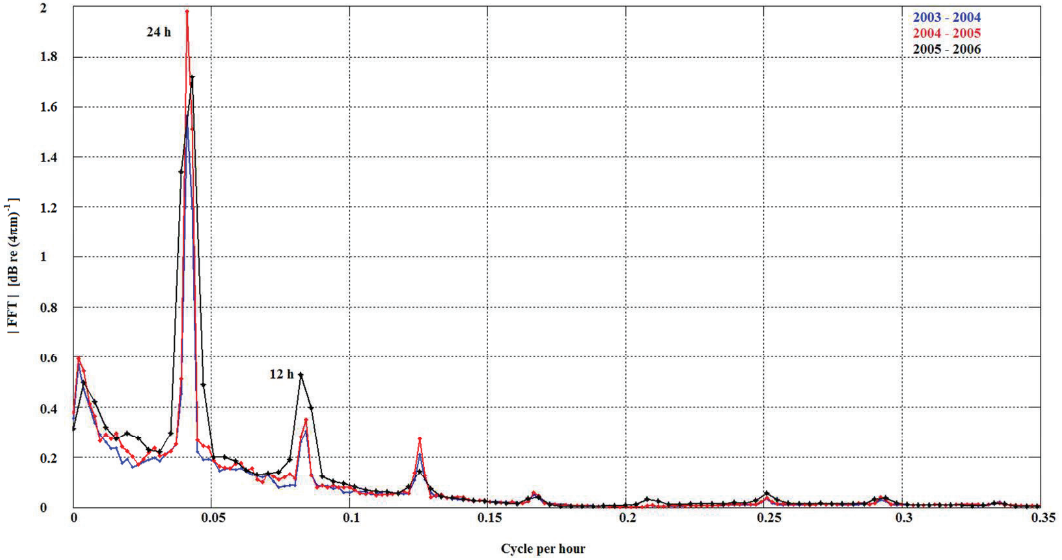

Fig. 9. Power spectrum for the three times series.

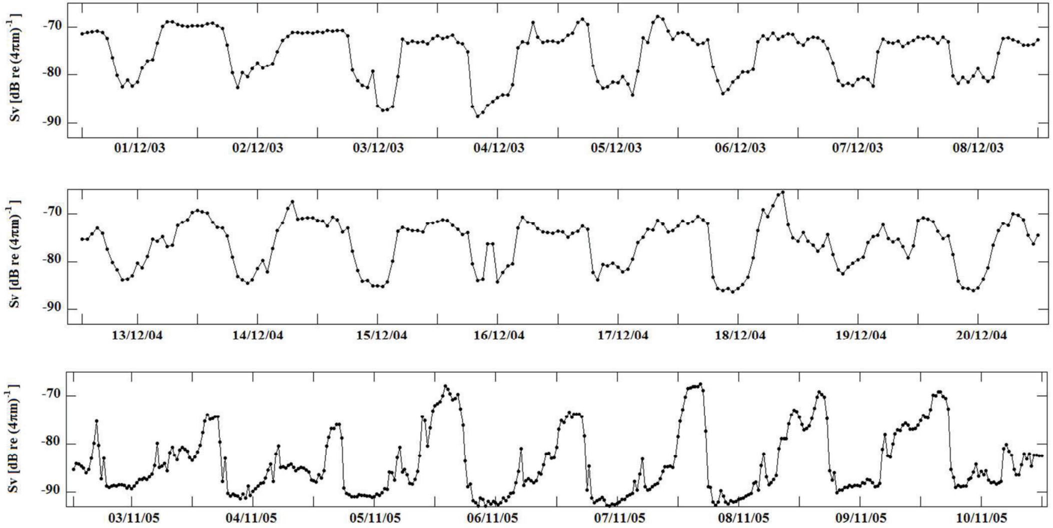

Fig. 10. Subset of backscatter strength hourly data in presence of twilight DVM pattern for the three deployments. Label at 12.00 UTC.

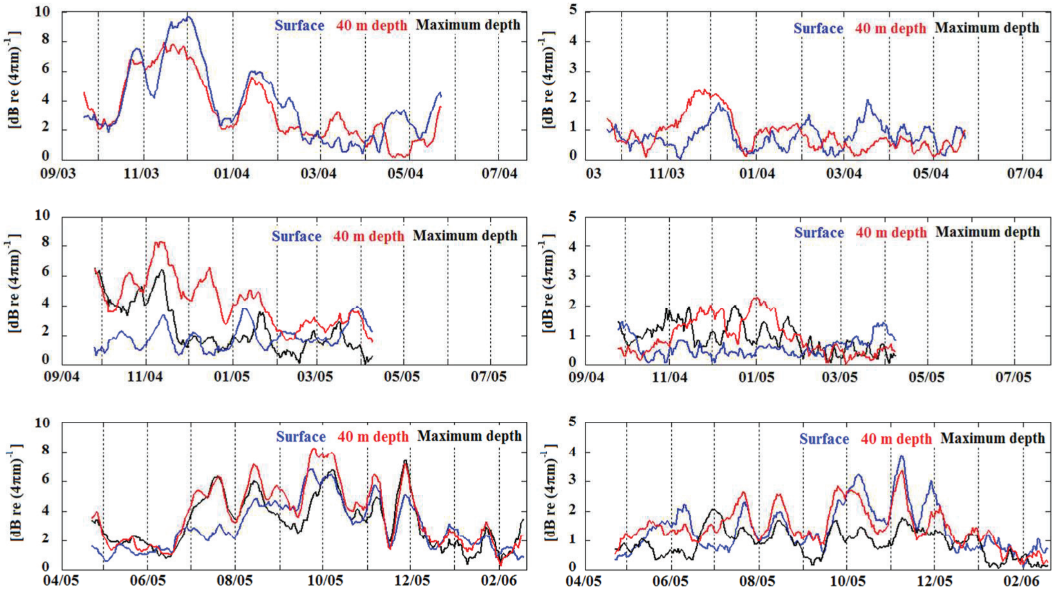

Fig. 11. Time evolution of the amplitude of the 24 h (on the left) and 12 h (on the right) harmonics at different depths.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
I◀
▶I
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

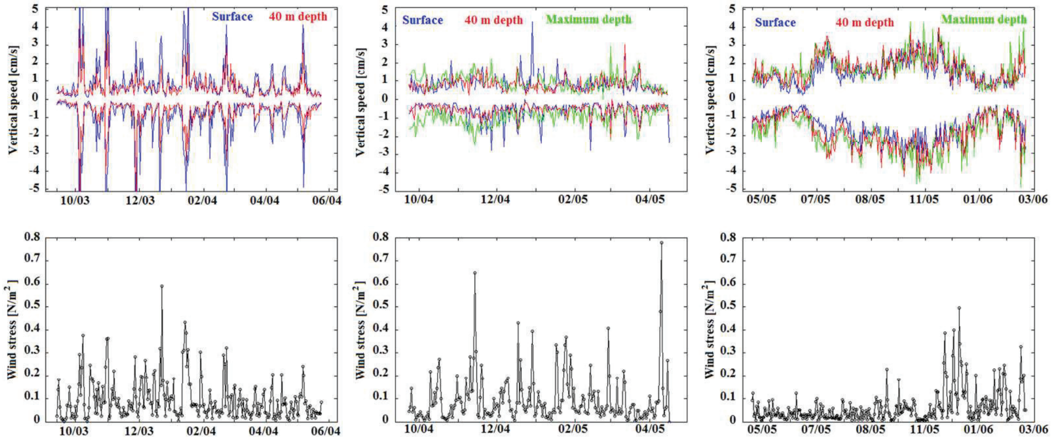

Fig. 12. Maximum and minimum vertical velocity (upper panel) and wind stress (lower panel) during the three deployments.