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Time frequency Analysis to Investigate Zooplankton Migrations in Terra Nova Bay Polynya (Ross Sea, Antarctica)

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Abstract

Time frequency analysis was applied to one-year long time series of acoustic Doppler Current Profiler (ADCP) ancillary data collected in Terra Nova Bay polynya (Ross Sea, Antarctica) to investigate the seasonal evolution of zooplankton migration in the area. An upward-looking 150 kHz narrow-band ADCP was operating in Terra Nova Bay (74°55.11' S; 164°20.4' E) at a sea depth of 600 m, from 5 February 2000 to 16 January 2001 and sampled the upper 160 m of the water column. Spectral analysis was performed on the mean backscatter strength time series by using a 240h-wide window moving at 1 day step. Assuming that the 24 hour period peak is associated with zooplankton diel vertical migration, the amplitude of the power spectral energy on this band was extracted from each spectrum and the time series of amplitudes analyzed. Results evidence four "migratory blooms", the first one occurring at the end of August and the others about every three weeks; the last one was at the end of October. Despite migrations are strongly reduced during the central summer period, from December to January, a clear signal is observed later, from late March until the beginning of the polar night. At the mooring latitude the last sunset occurs on 1 May and the polar night lasts until 13 August. The early occurrence of the first episode indicates that in the polynya, where the sun light penetration into the water is not prevented by the sea ice, the timing of the productivity is anticipated. Good relation was found between daily migration and solar cycles, but no clear evidence with the moon phase was revealed. Relevant differences in the migration patterns were observed between the upper and the lower layers. This method of analysis has proved to be simple but efficient to extract precious information to support long-term ecosystem dynamics and productivity studies even from non-dedicated low-resolution acoustic measurements such as those provided by the ADCP.

Keywords ADCP, polynya, spectral analysis, zooplankton migration, Antarctica, Ross Sea, Terra Nova Bay

1. Introduction

Terra Nova Bay is located in the western side of the Ross Sea, bounded South by the Drygalski Ice Tongue and it is characterized by the presence of a recurrent, latent heat polynya, having a mean size of about 6000 km^2 (Kurtz and Bromwich, 1985; Van Woert, 1999) and persisting also during winter. This area is of particular interest for climatic studies as dense water formed during winter, the so-called High Salinity Shelf Water (HSSW), contributes to the Antarctic Bottom Water (ABW) which is part of the large-scale thermohaline circulation (Assmann and Timmermann, 2005; Jacobs, 2004; Jacobs et al., 1985). Moreover, it hosts an important nursery area of the Antarctic silverfish (*Pleuragramma antarcticum*) (Vacchi et al., 2012), a colony of Adélie Penguins (*Pygoscelis adeliae*) in Adélie Cove and the large Emperor Penguins (*Aptenodytes forsteri*) reserve at Cape Washington (Kooyman et al., 1990). Due to its high ecological value, Terra Nova is an Antarctic Special Protected Area (Antarctic Treaty Secretariat, 2003). For all these reasons, the area has been object of scientific investigations since the beginning of the Italian Antarctic Program and was selected as location for the Antarctic scientific base Mario Zucchelli Station (www.pnra.it).

Polynyas are also peculiar areas for the polar marine life: being almost free from ice than the surrounding, at the end of polar night, the solar radiation immediately penetrates into the sea and produces an early warming and irradiance which enables to anticipate the seasonal phytoplankton production (Tremblay and Smith, 2007). The high primary productivity sustains a food-rich area for the higher trophic level (Karnowsky et al., 2007) thus attracting life up to the marine mammals, which also take advantage of these openings for breathing.

Since the zooplankton can be regarded as the trophic link between the primary production and the higher trophic levels, its knowledge is of relevant importance for many investigations. Nevertheless, there is still a lack of knowledge about zooplankton dynamic in the Southern Ocean, as the sea-ice coverage does not allow the in-situ sampling from research vessels during most of the year. In the Ross

Sea and in Terra Nova Bay, several experimental studies were carried out during the short austral summers (Azzali and Kalinowski, 2000; Carli et al., 2000; Pane et al., 2004) and trophic models have been developed (Pinkerton et al., 2010; Tagliabue and Arrigo, 2003,) but few long-term observations are available for the whole year. An important information about the zooplankton abundance during the annual cycle has been inferred from the analysis of faecal pellets collected by sediment traps (Accornero et al., 2003).

Acoustic measurements are often employed for the remote observation of the oceans and dedicated instrumentation working on a wide range of frequencies is now available for the detection of zooplankton of different size (Brierly et al., 2006; Briseño-Avena et al., 2015; Lemon et al., 2012). An additional resource of acoustic data consists of by-products from the Acoustic Doppler Currents Profiler (ADCP). Despite devised for 3D current measurements, ADCP also provides ancillary data, in particular the echo intensity profile, which is dependent on the presence of biomass, sediment and bubbles in the water column. The analysis of these data is widely used to support different scientific investigations (Gostiaux and van Haren, 2010), such as the detection of zooplankton migration (Flagg and Smith, 1989; van Haren, 2007), suspended sediments (Jourdin et al., 2014, Russo and Boss, 2012), sea surface conditions (Hyatt et al., 2008; van Haren, 2001). Their use proved to be of great advantage for long term investigation in the polar areas, where direct sampling as well as satellite measurements is hampered by the presence of sea-ice.

During 2000/2001, in the framework of the Italian Program of Antarctic Research (PNRA, 2001), ADCP measurements were carried out in Terra Nova Bay to investigate the upper layer dynamics (Cappelletti et al., 2010). The long-term measurements of echo intensity data collected by the 150 kHz ADCP were recovered and analyzed in order to provide new insight on zooplankton dynamic in the region. The use of acoustic measurements for these kinds of studies is generally limited to a qualitative or “visual” analysis. Methods based on time frequency analysis aiming at identifying the zooplankton migration patterns, their occurrence and their seasonal cycle are here applied to approach the time series processing in a more objective and automatic way.

2. Materials and methods

2.1 Experimental set up

An oceanographic mooring (D2) equipped with an upward-looking 150 kHz narrow-band ADCP was operating in Terra Nova Bay (74°55.11’ S; 164°20.4’ E) at a sea depth of 600 m, from 5 February 2000 to 16 January 2001 (Figure 1). The ADCP was located at a depth of 178 m and sampled the water column up to the surface. Samples were collected into 16 m-depth bins over a 1 h period at 60 pings per ensemble to reduce the standard deviation of each measurement. The first bin mid depth was 160 m.

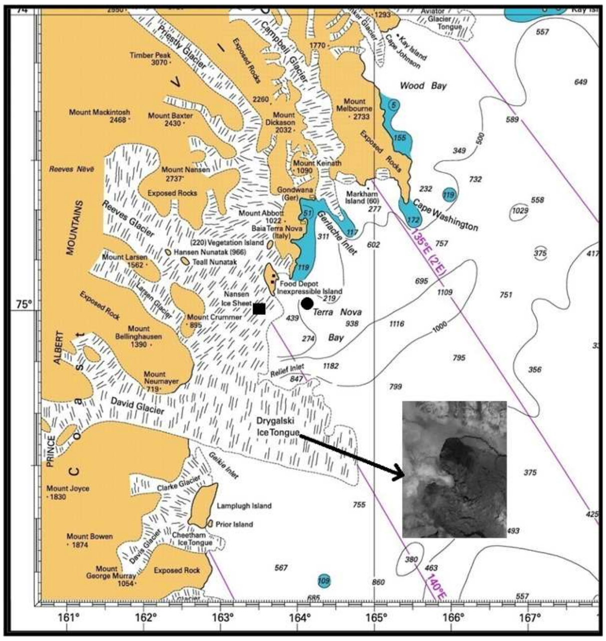

Figure 1. Map of the study area. Black dot and square correspond to the position of the D2 mooring and the Antarctic Weather Station ENEIDE, respectively. Satellite image taken on 29 September 2000 from ATSR-2 (Along Track Scanning Radiometer) provided by Rutherford Appleton Laboratory shows the Drygalski Ice Tongue and evidences the polynya area.

Two Aanderaa RCM7 eulerian current meters were also on the same mooring at 89 m and 179 m respectively. A second mooring (D1) equipped with eulerian current meters, temperature and salinity sensors was located in the same area (75°07.61’ S; 164°27.10’ E) at a sea depth of 1100 m and provided one year-long time series of temperature and salinity from fixed sensors located at a depth of 126 m and 526 m.

CTD casts performed during deployment and recovery operations provided summer temperature and salinity profiles in the area. Environmental conditions during the measurements period were obtained from the available oceanographic, meteorological and satellite observations.

Meteorological parameters, including wind speed and direction, atmospheric pressure and air temperature, were collected by the Antarctic Weather Station ENEIDE (74°42' S; 164°6' E), the closest to the area. The solar radiation was computed by MatLab@ air-sea toolbox version 2.0:8/9/99 while direct solar radiation measurements were available only from early November to mid February, during the operation period of the Italian Antarctic Base. Sea ice concentration data were obtained from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and Defense Meteorological Satellite Program (DMPS, USA) SSM/I passive microwave analysis archived at the National Snow and Ice Data Center (Cavalieri et al., 2008).

2.2 Environmental condition during the experiment.

Satellite data of sea-ice coverage and concentration allowed to estimate the temporal evolution of the Nova Bay polynya extension and to verify whether the sea surface on the mooring location was free from sea-ice. The temporal series of sea-ice concentration data in the *pixel* closest to the position of the mooring evidenced that the area was never completely covered by ice during the whole period of measurements. Greatest sea ice concentration was observed from June to October, while during February sea-ice coverage was below 20%. Strong katabatic winds flowing from the West and associated to an increase in the air temperature characterized the area, favoring the maintenance of the polynya. On the contrary, a relative increase of the sea-ice concentration was observed after periods of low winds, as occurred during the second half of May or during mid-March.

Sea currents were mainly barotropic, directed towards Northeast with a mean speed of about 30 cm/s; from February to April they had a lower speed and were directed eastward. In the upper layer, the currents were strongly driven by the wind, reaching hourly mean velocity of about 70 cm/s. Greater speed and variability in the vertical velocities occurred in the surface layer, particularly on December, notwithstanding the low wind intensity registered during that period. At deeper depths, along the whole water column, greatest vertical velocities were observed between June and October, in correspondence with the increasing of salinity associated to the episodes of dense water formation, while a lower vertical dynamics characterized the summer, from December to February.

Sea temperature and salinity time series were available at the depth of 126 m during the whole period of the experiment. Some evidences of the mixing of the ice melted waters are detected even at this depth, where salinity reaches the minimum (34.54) only at the end of May, while the maximum (34.76) occurred on October. At the same depth, sea water temperature was constant at -1.92 °C from late March to the end of November. Summer warming and the mixing with surface warmer water have negligible effects at this depth as the sea temperature hardly reaches -1.8 °C on December. As the results of the ice melting, summer CTD casts evidence a surface layer with salinity lower than 34 and slightly warmer waters just above the zero degree which help to enhance the generally weak vertical stratification. During winter, uniform temperature close to the freezing point, strong mixing and dense water formation processes make the water column vertically instable.

At this latitude, the polar night lasts from 29 April to 11 August and midnight sun period is from 3 November to 8 February. During this period daily mean data of computed solar radiation gives more than 500 W/m^2, with a maximum value of 884 W/m^2.

2.3 ADCP Data quality check

The general quality check, based on the analysis of the parameters provided by the instrument, had been performed when approaching the analysis of the currents data (Cappelletti et al., 2010). In particular, pitch, roll and tilt angles data were all below the limits provided by the manufacturer, thus assuring that the mooring maintained the vertical position despite the strong currents in the region; also the so-called "percent of good data", a key quality control parameter which summarizes the results of a series of internal test on the instrument performances indicating what fraction of the pings passed the various error thresholds, confirmed the good quality of the collected data (Teledyne RDI, 2011). An additional quality check was performed on echo intensity data before computing the Backscatter strength to detected outliers, gross errors, and not coherent data. In particular, the tests have ruled out any noise on the data due to the presence of the eulerian current meter that was located on the same mooring at 86 m depth.

As expected, the mean profiles of echo intensity data for each beam signal is characterized by a decreasing with the increase of the distance from the source, while for those close to the sea surface (bin 10-11) the effects of the air-sea interface are prevalent, leading to an increase in the signal. The relative standard deviation tends to increase approaching the surface, reaching the maximum (19% of the signal) in bin 10. Data for the bin 11, at the air-sea interface, was discarded according to the manufacturer indications as it is too strongly affected by the sea surface.

2.4 Backscatter strength computation

Hourly data of mean backscatter strength (Sv) were computed according to the formula based on the sonar equation (RDI, 1998) and following Blanc et al. (2008).

Echo intensity amplitude registered by the instrument depends on its technical characteristics and on the sampling setting. The formula was devised to obtain absolute physical data (backscatter strength), thus allowing the comparison among different data set as well as instrument calibration when used to detect environmental parameters of interest such as zooplankton biomass or suspended sediment concentration (Fielding et al., 2004).

Due to the lack of the concurrent time series of temperature and salinity profiles for the whole period, constant values of sound speed velocity and sound absorption coefficient were obtained from the data collected by the mooring and from summer CTD casts.

The influence of the variability of temperature and salinity on this computation was assessed.

The variability of temperature and salinity observed during the year affects the sound speed just in the upper 50 m and occurs during the short melting period. Temperature variability in the upper layer is limited to few degrees, salinity to less than 1 psu. Moreover, the effects of the increasing depth on the sound speed were limited to 2 m/s as the water column sampled by the ADCP was between the surface and 160 m depth.

The absorption coefficient of water was computed according to Ainslie and McColm (1998) using constant values T=−1.9°C, S=34.6, pH=8, z=80 m. Also in this case the limited range of variability of these parameters has a small influence on the values of the coefficient. As an example, a difference of 1°C in temperature results in a variation of the coefficient of less than 3%, while the effects of salinity and depth variations are even more negligible.

A test was performed comparing the Sv profile computed at the beginning of the experiment (February 5, 2000) using the temperature and salinity profile collected close to the mooring just before the deployment and the Sv profile computed using constant values. Despite the CTD profile was taken at the end of the melting season, when the maximum vertical variability can be expected, the difference between the two computed profiles was really negligible, less than 10^{-3} of the signal.

Computation of Sv was done for each beam as follows and then the four sets were averaged.

$$S_V = 10\log\left(\frac{4.47\cdot 10^{-20} K_2 K_S (273+T_x)\left(10^{(K_C(E-E_R)/10} - 1\right)}{cPK_1 10^{-2\alpha R/10}} R^2\right)$$

$$R = \frac{B + \left(\frac{P-D}{2}\right) + nD + \frac{D}{4}}{\cos\vartheta}\frac{C'}{C}$$

where

Sv is the backscattering strength in dB re $(4\pi m)^{-1}$,

R is the range to the scatterers along the beam (slant range),

$\alpha = 0.0298$ is absorption coefficient of water (dB/m),

$\vartheta = 20°$ is the beam angle of the ADCP

$n = 1...10$ is the cell number

B = 10 m is the blank distance

D = 16 m is the depth cell

C = 1442 m/s is the sound speed at the ADCP

C' = 1440 m/s is the average sound speed on the water column

E is the raw echo intensity measured by the ADCP

E_R = 55 count is the reference level for the echo intensity obtained as the minimum recorded values of the bin closest to surface.

$K_c = \frac{127.3}{Tx + 273}$ dB/count is the conversion factor for eco intensity

K_2 = 3.6 system noise constant as provided by the manufacturer

Ks = 4.17 10^5 is a constant depending on the ADCP frequency

K_1 = 3.9 W is the transmit power as provided by the manufacturer

P = 16 m is the transmit pulse length,

Tx = -1.9 °C is the sea temperature at the transducer

2.5 Time frequency analysis

Time frequency analysis is a powerful tool to investigate the occurrence and the temporal evolution of phenomena that can be identified by a specific periodic behavior.

Although other factors are not distinguishable from one another using a single-frequency device, acoustic backscatter measurements from ADCP allow for the recognition of the presence of zooplankton as it is characterized by a strong daily or sub-daily periodic variability. For this reason time frequency analysis was successfully used to investigate long-term ADCP backscatter measurement in the Ligurian Sea (Bozzano et al., 2014)

Backscatter signal due to zooplankton migration can be modeled as a 24 h period square-wave like form. The contribution of the twilight migration, typical of zooplanktonic organisms which repeat their migration from surface layers to greater depths twice a day, is generally of less importance and can be identified by a 12 h minor peak in the spectrum. As known, the Fast Fourier Transform (FFT) of a symmetric 24 h square wave has the maximum at the principal harmonic but also a series of minor peaks on the odd harmonics T/(2n+1), namely 8 h, 4.8 h.., whereas even harmonics (12 h, 6 h,…) appear when the duty cycle is different from 0.5. This explains the series of peaks in the power spectrum of a 240 h backscatter sample reported in Figure 2.

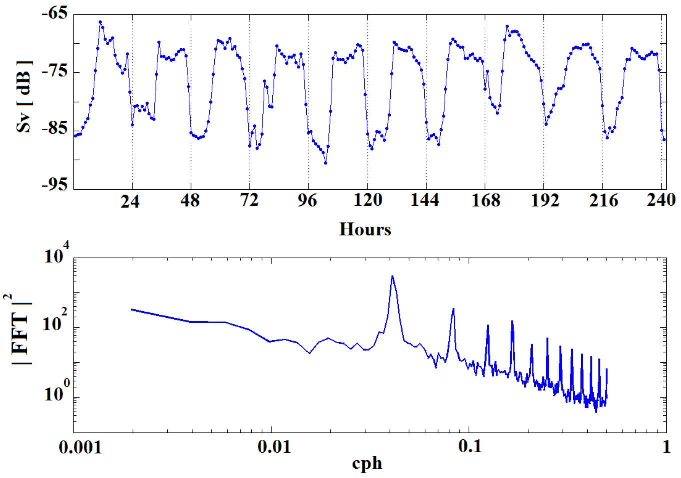

Figure 2. A sample of 10 days of backscatter strength and the relative power spectrum.

In the case of the polar regions, the duration of the night and day strongly changes during the year and this may influence the daily migration cycle, leading to a highly asymmetric 24 h wave. In this case, the resulting spectrum would be characterized by secondary peaks on both even and odd harmonics. The presence of the 12 h peak due to the different duty cycle could mask the contribution to the backscatter related to the twilight migration pattern of the zooplankton, so that the results interpretation require particular attention.

Simple tests have been performed with the aim to avoid misleading interpretation of the data. Three cases have been considered: a symmetric 24 h period square wave (duty cycle 50%), an asymmetric 24 h period square wave (duty cycle 62%), and the sum of symmetric square waves (duty cycle 50%) having 24 h and 12 h period respectively, the last one with an amplitude of 30% of the first and 6 h phase shift. Random noise having an amplitude of one tenth of the 24 h square wave amplitude was added in all three cases (Figure 3 left). FFT analysis was then performed on the three samples (Figure 3 right). It can be noted that the 12 h peak which appears in the FFT spectrum of case b is just the effect of the 62% duty cycle of the original 24 h square wave, which is also greater than the one of the case c, resulting from the presence of a 12 h component in the analyzed signal.

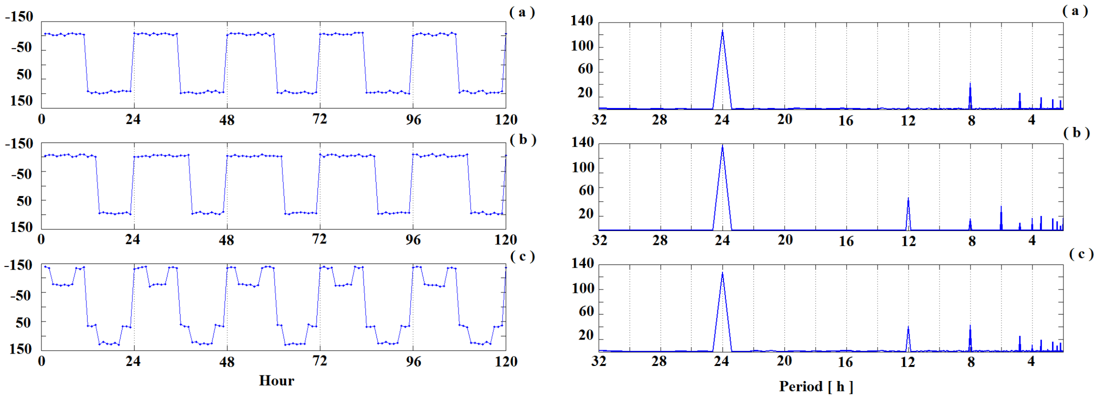

Figure 3. Simulated signal and relative FFT spectrum for the three cases: a) 24 h period square wave with duty cycle=0.5; b) 24 h period square wave with duty cycle=0.62; c) sum of 24 h and 12 h period square waves with duty cycle=0.5

Time frequency analysis of backscatter strength data was performed on 240 h-long samples selected with a centered window moving at 24 h step. Ten days were the best compromise to resolve the frequencies of interest, a wider window would ensure a better spectral resolution but would reduce the temporal resolution, being each spectrum representative of a too long interval period. Before the FFT analysis each sample was de-trended to limit the contribution of the lowest frequencies. Data were processed at all bin levels.

3. Results

3.1 Seasonal variability

Echo intensity data measured by acoustic devices are the result of the amount and type of scatterers present in the ensonified volume of water, in particular suspended sediments, biomass, and bubbles. It is also known that strong winds, ocean fronts and turbulence, as well as the presence of sea surface or bottom interfaces affect the backscatter signal (Visbeck and Fisher, 1995) in different ways. The time series of daily average backscatter strength profiles (Figure 4) is firstly analyzed to identify possible causes influencing the backscatter intensity.

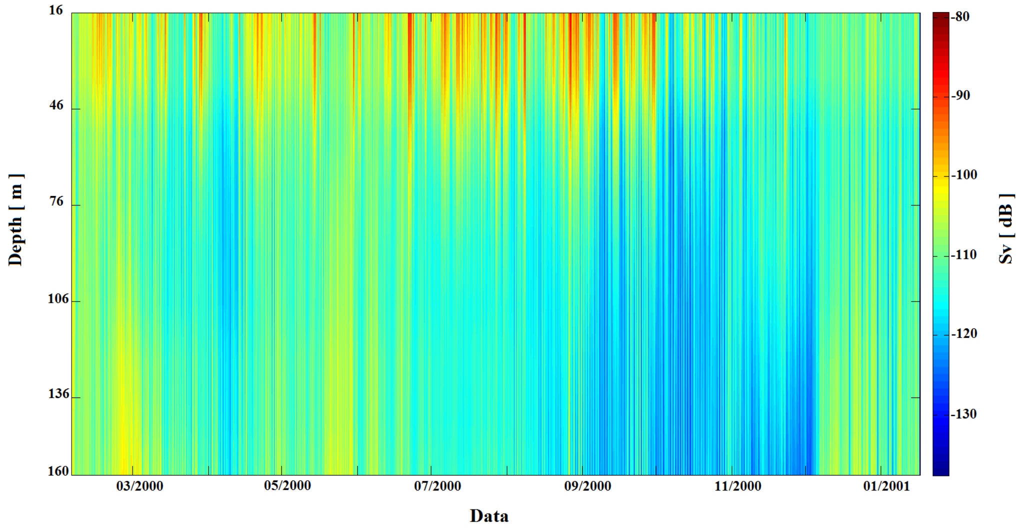

Figure 4. Temporal variability of the acoustic backscatter strength during the entire period of measurements.

For most of the examined period, the data can be divided in two groups according to common features, as proved by the degree of correlation (Table 1): upper (7-10) and lower (1-4) bins, corresponding to the upper 60 meter of the water column and to the layer between 100-160 m depth, respectively. Unfortunately, no deeper measurements were available so that a lower depth limit could not be set.

1	2	3	4	5	6	7	8	9	10	
1	0.94	0.87	0.73	0.6	0.49	0.26	0.52	-0.04	-0.12	1
	1	0.97	0.86	0.72	0.57	0.28	0.03	-0.09	-0.13	2
		1	0.95	0.85	0.70	0.38	0.08	-0.08	-0.10	3
			1	0.96	0.82	0.51	0.14	-0.05	-0.07	4
				1	0.93	0.64	0.27	0.03	0.02	5
					1	0.86	0.53	0.28	0.26	6
						1	0.86	0.67	0.61	7
							1	0.93	0.86	8
								1	0.92	9
									1	10

Table 1. Correlation matrix of backscatter strength. Correlation coefficient greater than 0.6 are highlighted.

Greater variability and greatest values are observed in the upper layers, particularly during winter months. A quite good correspondence between wind kinetic energy peaks and backscatter strength in the surface layer is found especially in the period February – June, when the correlation of the two series is greater than 0.5. Nevertheless, the strongest winds, such as those blowing during winter months, do not seem to affect the echo intensity as expected. This may be due to the effects of sea ice at surface that modifies the relation between the wind and the acoustic backscatter strength. On the contrary, the decreasing in the backscatter strength values during low wind periods, in particular starting from December, when the lowest wind intensities occurred, is well evident (Figure 5).

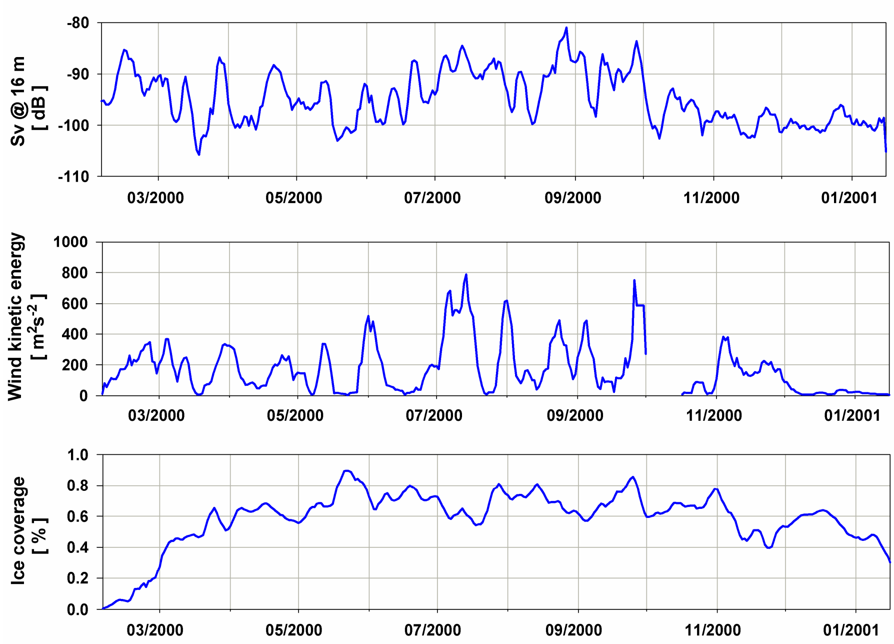

Figure 5. Time series of daily observations of backscatter strength at 16 m depth, wind kinetic energy and sea ice coverage during the whole measurements period.

Seasonal trend is opposite in the deeper levels: greatest values are recorded during summer, in particular on December and January, and, at a less degree, up to mid-March. Great values are also found during the last two weeks of May, following a period characterized by very low backscatter intensity. Lower values are more frequent in April and from September to late November. In many episodes relative minima are common to all layers.

Spectral analysis was performed on the whole series of hourly mean backscatter for each level on 34 adjacent subsample of 240 hours to focus on sub-daily variability and then averaged to increase the confidence level (Figure 6). Apart from the upper level which is dominated by a red spectrum with the peaks less pronounced, the other averaged spectra have almost the same features, presenting the maximum on the 24 h harmonic, a secondary peak on 12 h and a series of peaks on higher harmonics.

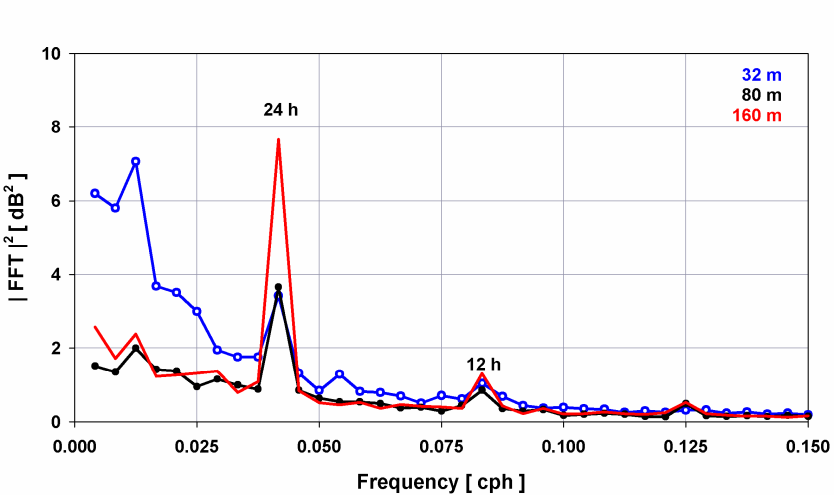

Figure 6. Power spectrum of the backscatter strength at 32 m, 80 m and 160 m depth as the average of the FFT performed on 34 adjacent subsample of 240 h (ten days).

In order to evaluate the temporal evolution of the two main evidenced harmonics, time frequency analysis was performed as described in 2.5. The amplitude of the 24 h and 12 h harmonics were extracted from each spectrum obtaining the temporal series of the two amplitudes, for each depth. The vertically integrated time series of amplitudes, superimposed to the computed solar radiation and the moon phase, are shown in Figure 7 and well evidence the main features of the migratory phases of zooplankton in the area.

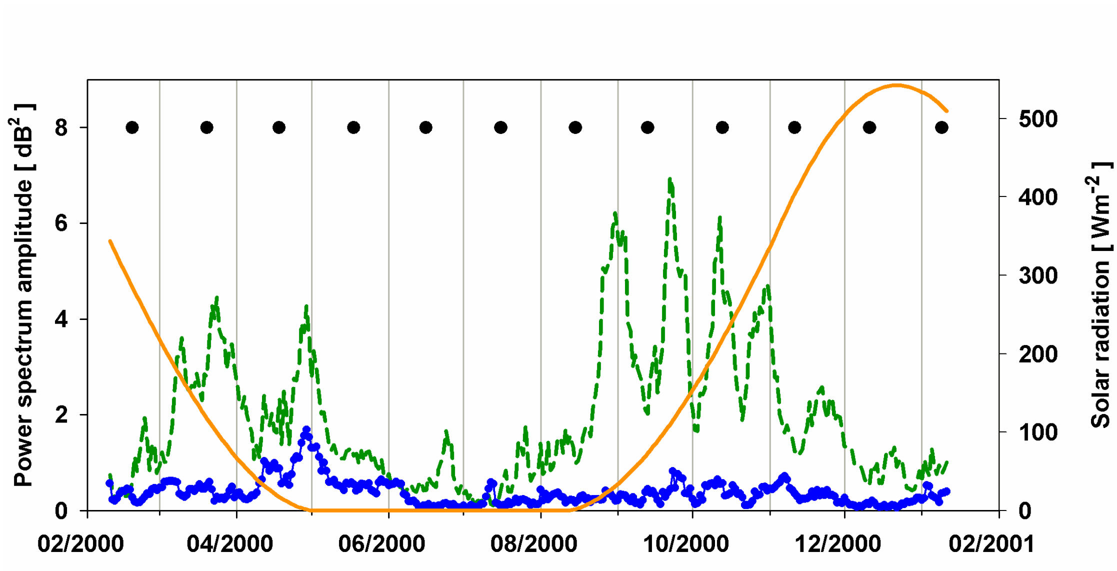

Figure 7. Temporal evolution of computed solar radiation (orange line) and the vertically integrated amplitude of the 24 h (dashed green line) and the 12 h (dotted blue line) harmonics. Black dots represent the full moon on the mooring site.

Four major episodes characterize the presence of zooplankton seasonal migratory patterns. The first one occurs at the end of August and lasts about ten days, the others approximately every three weeks, the last being at the end of October. Vertical daily migration is strongly reduced from late November to early March, when the solar radiation has the greatest values and day length is maximum, and from early May to mid-August, during the polar night (at the mooring latitude the polar night lasts from 1 May to 13 August) apart from a small relative peak at the end of June. The amplitude of the 12 h signal is quite low even in correspondence of the highest 24 h peaks; the main peak is at the end of April in correspondence of a relative maximum of the 24 h amplitude time series.

The analysis of the spectrograms (Figure 8) evidences the existence of some relevant differences between the upper and the lower levels. The values of the correlation coefficient of the 24 h amplitude time series indicate a great correlation in the layers from 160 m to 96 m depth (coefficients are from 0.92 to 0.6) while, on the contrary, they are totally uncorrelated with the upper layers (coefficients below 0.2). In the upper layers, only the time series at 64 m depth reaches the values of 0.7 with the adjacent levels at 80 m depth and 48 m.

Whereas the major four 24 h peaks dominate in the lower layers, the signal around 80 m depth has the first maximum during the second half of September, in correspondence with the second major peak of the deeper levels, followed by minor peaks about each two weeks. At the same depth maxima having comparable amplitude and lasting about two weeks can be also observed between March and June, the most significant centered at the beginning of May.

The amplitude of the 12 h harmonic is generally lower and has different temporal evolution. Twilight migration seems prevailing on April and May and at intermediate depths, between 64 and 112 m. 12 h peaks of particular importance are observed on May at 80 m depth and on mid November at the deepest level.

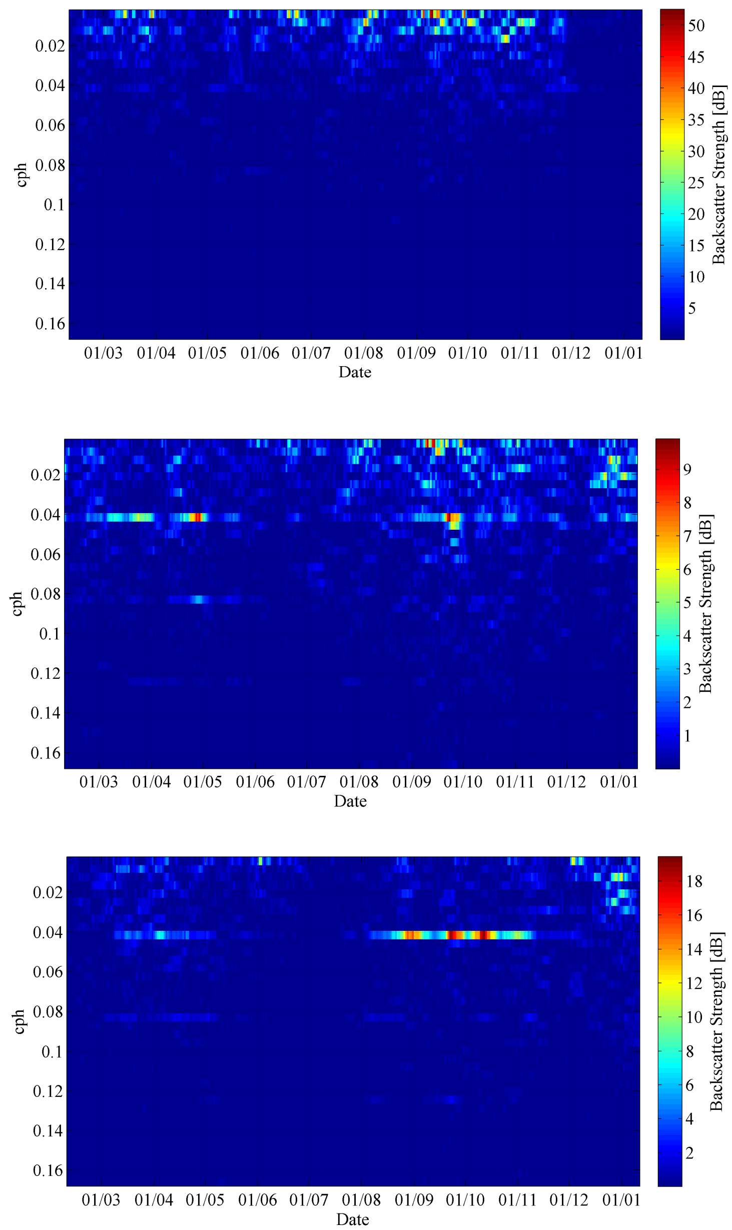

Figure 8. Spectrograms of backsatter data at 32 m , 80 m and 160 m depth.

3.2 Migratory patterns

To better characterize the migration patterns, the analysis was performed on several sub-sets of hourly backscatter strength data collected in correspondence with the most evident 24 h and 12 h peaks of the spectrogram. To reduce high frequency variations and noise, data were smoothed with a centered three points moving average. Three series of data correspondent to the mid depth cell of 160, 80 and 32 m, respectively, were chosen as representative of deep, intermediate and surface levels. During the first case study, backscatter signal at 160 m (Figure 9 a) evidences the strong link between the daily variability and the solar radiation cycle. Nights last from 18 to 14 hours and the peak of the solar radiation is quite low, increasing from 93 to 256 Wm^{-2} during this 20 days period. Absolute minima of backscatter signal at 160 m exactly occur in correspondence with the short daily light maximum and all have similar values. During the night, the cycles differ more from each other's: the values of maxima change and relative minima, indicating a minor contribution of twilight migrations, sometimes are very well pronounced, sometimes hardly appear. In the upper layers, a daily cycle can be clearly identified only at the end of the examined set when the backscatter strength shows comparable values in the water column indicating an upward movement of the whole zooplankton mass which affects the entire water column monitored by the ADCP.

In the second week of September, the absolute minima, when present, tend to anticipate the maximum of solar radiation. Three weeks later (Figure 9 b) the nights become shorter, lasting from 10 hours to only 5 at the end of the period, and the solar radiation increases from 447 to 596 Wm^{-2}. Again, there is a very good correspondence between absolute minima of the backscatter signal at 160 m and maxima of the solar radiation. However, now the diurnal relative maxima are more evident and the nocturnal relative minima are generally smoothed than in the previous set. The backscatter strength at the intermediate depth doesn't show a well marked diurnal cycle for all the period indicating that zooplankton tends to remain stable near the surface.

The third selected set (Figure 9 c) is in correspondence with the maximum of 24 h harmonic obtained by the time frequency analysis for the upper level, from November 11 to December 1, during the austral summer period. Solar radiation peaks span from 760 to 850 Wm^{-2} and midnight values increase from 60 to 160 Wm^{-2}. Daily cycle in the upper layer is more evident in this case and the amplitude is comparable with that observed in the deeper level in correspondence of the spring case study, but the signal is never so clear. As also suggested by time frequency analysis, in the deeper level the daily cycle signal shows reduced amplitude and it is poorly defined.

During the autumn season (Figure 9 d) a clear semidiurnal cycle is present in the backscatter strength of intermediate level and deep layer and it is prevailing on the 24 h periodic migratory pattern in correspondence with a limited food concentration in agreement with the observations made by Godlewska (1996).

In winter (Figure 9 e), no migratory pattern is evidenced, but in the intermediate and surface levels the signal shows some variability that might be ascribed to the presence of larvae dwell near ice edge (Daly,1990).

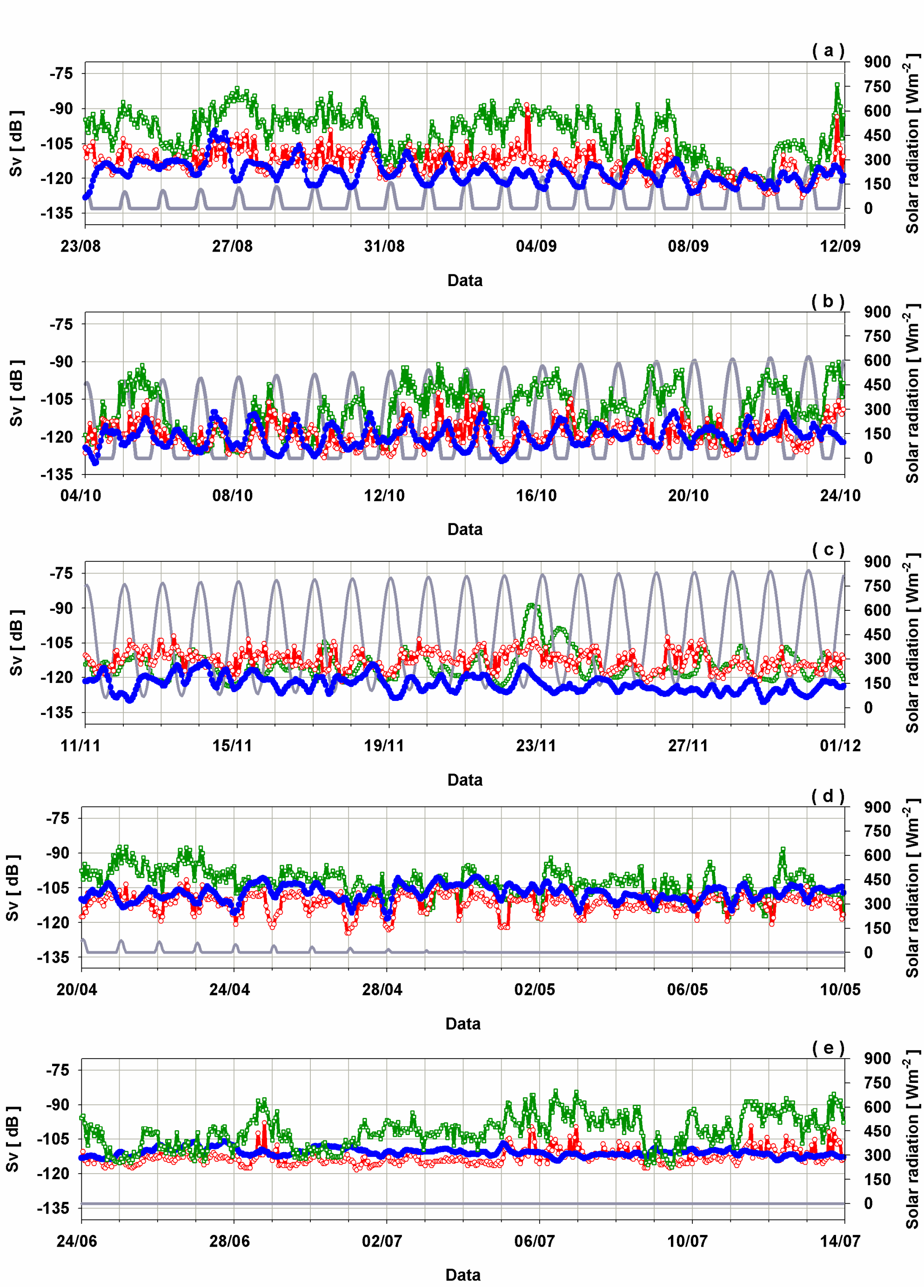

Figure 9. Time series of 20 days sub-samples of backscatter strength at 160 m (full dotted blue line), 80 m (empty dotted red line) and 32 m (empty square green line) depth superimposed to the temporal evolution of solar radiation (grey line).

3.3 Diel variability

The analysis on the migratory phases of zooplankton shows the strong relationship with the variation in the duration of day time, however differences in light intensity might be counted among the causes of the 24 h upward and downward movements.

The diel variability is well detectable comparing the average of the Sv for each hour to the sunset and sunrise: zooplankton moves towards the surface at the sunset and vice versa near the sunrise in all the period in which the sun alternation occurred at the mooring site.

The same case studies chosen to investigate the migratory pattern has been selected except for the case c, corresponding to midnight sun period.

From the end of August to the middle of September (Figure 10 a) sunset and sunrise occurred between 4:11 to 6:17 UTC and between 21:54 and 19:37 UTC, respectively. The diel cycle is well marked in the deepest layer where the most relevant upward movement is in the correspondence with sunset and the downward of sunrise. The Sv at 80 m and 32 m depth shows the same dynamic with an ascent around 6:00 UTC (about two hours after sunset), a downward movement around 15:00 UTC followed by a small cycle of 4 hours and the decrease around sunrise. The duration of the circadian cycle is similar to the sunlight cycle with nighttime lasting about 13 hours.

In the following month (Figure 10 b) nighttime decreases, sunset occurred from 8:13 to 10:36 UTC and sunrise spans from 17:27 to 14:56 UTC. The curve corresponding to diel variability at 160 m depth has the same gaussian shape of the previous period but it is narrower and again the most sharp movement upward and downward occurred near sunset and sunrise, respectively. Sv at 80 and 32 m depth shows lower values than in September but a more marked diel cycle and only during nighttime, backscatter strength at intermediate depth is higher than those at the deepest level.

One month after the March equinox (Figure 10 c) is getting dark, but zooplankton migration followed again the diel cycle with movement upward close to sunset and downward close to sunrise. The time series of all the three selected depths shows the same trend, with a sharp ascent after the sunset to 8 UTC, followed by quite constant values until one hour before sunrise, when occurred a drop. Backscatter strength values at 80 m depth are lower for all analyzed periods with respect to the deepest level and shows the most wide diel cycle.

During austral winter, when no sun light is present (Figure 10 d) no migration occurred, the backscatter strength at each level can be considered quite constant, very small variation can be seen except for some movements in the upper level that can be ascribed to the presence of larvae.

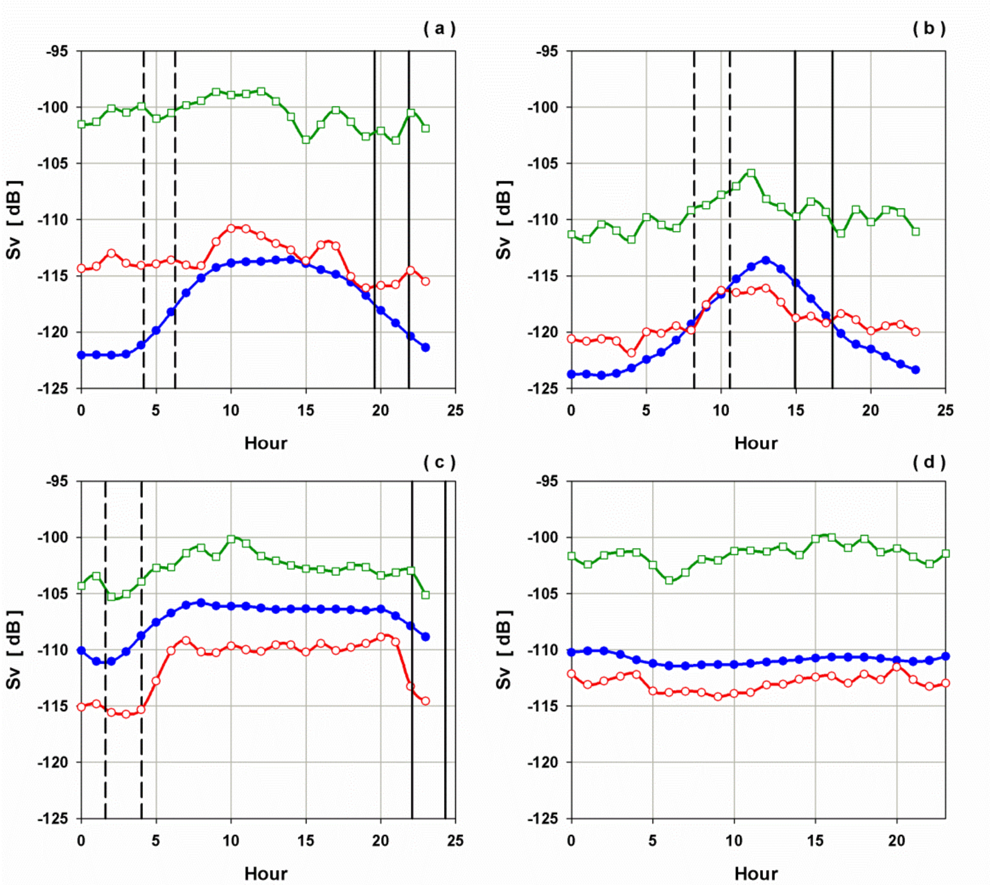

Figure10. Averaged diel cycles at 160 m (full dotted blue line), 80 m (empty dotted red line) and 32 m (empty square green line) depth for the following periods: a) 23/8 -12/9; b) 4/10-24/10; c) 20/4-10/5; d)24/6-14/7. Vertical lines indicate sunset (dashed line) and sunrise (solid line) at the beginning and the end of each period.

4. Conclusions

Acoustic backscatter data collected with an ADCP deployed in Terra Nova Bay during 2000 and sampling the water column up to a depth of 160 m, were recovered and re-analyzed with the aim to investigate the zooplankton migrations.

The sampling time (1 hour) of the available dataset was lower than what generally used for these kinds of studies, but sufficient for the spectral analysis; differently from multi-frequency acoustic devices employed for bio-acoustic observations, the ADCP was working only at 150 kHz but this was quite appropriate to address the study of macro-zooplankton and krill which represent an important part of the Antarctic zooplankton. So, even the ADCP data were originally collected for completely different purposes, the use of time frequency analysis allowed to extract useful information about the zooplankton dynamics in the area during one entire year.

With the assumption that the variability of backscatter at 24 h and 12 h period is related to the migration of zooplankton, the study of the temporal evolution of the time series of these amplitudes obtained by FFT analysis was used to describe the seasonal cycle of zooplankton.

Signal ascribed to daily migration generally dominates in the examined time series and reaches greater values. Significant differences are observed between the upper and deeper examined layers both in terms of presence and migration pattern. In deeper layers daily signal is prevailing but the presence of sub-daily migration pattern can be observed quite often. Furthermore, high amplitude of the 24 h and 12 h signals occur even when the measured backscatter data are low, such as during September and October, while are not observed during December and January, when the backscatter data reaches their maximum values.

Daily migration initiates late August, just after the end of the polar night, reaches the maximum at the beginning of September and then decay. Differently from the ice-covered areas around the polynya, the sun light immediately penetrates in the water thus explaining the early occurrence of the first observed peak. Other three periods of intense migration lasting about ten days follow this first period of intense movement until mid November.

The occurrence of two phytoplankton blooms in Terra Nova Bay, one between December and January and the second on February, have been reported by Innamorati et al., (2000). Usually, they are followed by an increases in the zooplankton biomass as the greatest values of the observed backscatter strength may suggest. However, no relevant signals of the daily migrations were detected until the end of February. Cisewski et al., (2010) found similar results in the Lazarev Sea and ascribed the strong reduction of migration signal during December- January to a decreasing of the zooplankton population in the examined water column or to a strong reduction of the migration activity due to the limited difference in the daily solar radiation cycle. Cottier et al. (2006), refer about a chaotic up and down movement to feed and to escape from predators.

During winter, due to the scarcity of food resources in the water column, zooplankton species tend to limit their migration and to remain in a state of quite metabolic depression (Nicol, 2006) or to feed on the seabed that is rich of organic matters (Smith and Demanster, 2008).

During late summer and fall season zooplankton migrates downward in the deepest layer and a daily cycle is well detectable.

The good correlation between the solar cycle and migration pattern was common to all examined depths but no evident relation between the time series of 24 h and 12 h period amplitudes and the full moon phases could be found. Although zooplankton migration is strongly related to seasonality and daytime length, a good correspondence between the ascending/descending movement and the sunset/sunrise was found.

In all periods characterized by an alternation of sunrise and sunset, the backscatter strength of the deepest layer shows a clear 24 hour pattern with an increase from sunset up to three or four hours later, a flat shape depending on the nighttime duration and a sharp decrease near sunrise. The same trend is identifiable in the upper levels, but less marked and with more variability during the nighttime period.

Time frequency analysis of a long time series of backscatter data allowed identifying in automated and objective way sub-sets of the signal containing significant information for the analysis of zooplankton migrations, that were then selected for a more detailed analysis. The good correspondence between the spectrogram results and the observed migration patterns proved how this method of analysis is simple but efficient to extract precious information even from signals which may have poor spatial and temporal resolution. Moreover, it was verified that the possible effects of the uneven duty cycle and of the non sinusoidal shape of the signal on the spectral analysis did not affect significantly the results.

Long-term acoustics data, also obtained from non-dedicated, low-resolution measurements such as those of the ADCP, can provide additional time series of relevant biological data which are of advantage for ecosystem dynamics and productivity studies. They are of particular values in the polar regions where direct observations are scarce and difficult to be obtained and should then be included into the existing monitoring observing systems.

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