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Due to the lack of contemporary in-situ net samples, results are more qualitative than quantitative,. nonetheless, demonstrate the skill of the method to extract relevant information even when applied to data of a non-devoted low-resolution system.
This could be of particular interest in polar areas where it is difficult to perform a continuous biological monitoring, but long time series of acoustic Doppler current profiler data may be available.

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

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Abstract

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Moreover, the migration patterns in the upper and the lower layers showed significant differences.

Due to the lack of contemporary in-situ net samples, results are more qualitative than quantitative,. nonetheless, demonstrate the skill of the method to extract relevant information even when applied to data of a non-devoted low-resolution system.

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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) that 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.

Polynyas are also peculiar areas for the polar marine life: being almost free from ice, at the end of polar night, the solar radiation immediately penetrates into the sea and produces an early warming and irradiance that enable 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.

The zooplankton can be regarded as the link between the primary production and the higher trophic levels. Notwithstanding its relevant importance, the studies on this fundamental component of the Antarctic ecosystem are still limited, mainly owing to the lack of long time series of continuous data. In fact, the sea-ice coverage does not allow the in-situ sampling 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. Thus, many important information about the zooplankton abundance during the annual cycle are achieved by indirect observations, like those obtained from the analysis of fecal pellets collected by sediment traps (Accornero et al., 2003).

Acoustic measurements are widely used 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 (Brierley et al., 2006; Briseño-Avena et al., 2015; Lemon et al., 2012). An additional resource of acoustic data consists of by-products from Acoustic Doppler Currents Profiler (ADCP). Despite devised for 3D current measurements, ADCP also provides ancillary data, in particular the echo intensity profile that is dependent on the presence of scatterers (e.g., biomass, sediment, bubbles) in the water column. The analysis of these data has been successfully applied in 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).

Use of ADCP data could also prove of great advantage for long term investigations in the polar areas, where direct sampling as well as satellite measurements are 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). In order to provide new insight on zooplankton dynamic in the region, particularly on the migration patterns, their occurrence and their seasonal cycle, the echo intensity data collected by the ADCP were examined in both time and frequency domains.

The method described here allows for performing the analysis of the ADCP ancillary time series in a more objective and automatic way than those generally in use, which are primarily based on visual and qualitative assessments.

The lack of concurrent biological samples did not allow an in-situ calibration of the raw echo intensity data provided by the ADCP. Consequently, the application of spectral and time-frequency methods to the backscatter strength data is suitable only to identify vertical migratory patterns of zooplankton. In spite of this, the results can still give important indications on the behaviour of some specific taxa of the area during the experiment.

Furthermore, this method of analysis can be applied to historical time-series of ADCP data taken in the area for other purposes to deepen the knowledge of Antarctic zooplankton especially during winter periods where net samples cannot be easily performed.

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) from 5 February 2000 to 16 January 2001 (Figure 1). The mooring was deployed at 600 m sea depth and the ADCP was mounted at a depth of 178 m and set to sample the water column up to the surface by using a vertical resolution of 16 m. The mid depth of the deepest level was 160 m. The ping frequency was set at one minute. To reduce the standard deviation of each measurement, the instrument was programmed to provide output data obtained as average over one hour period.

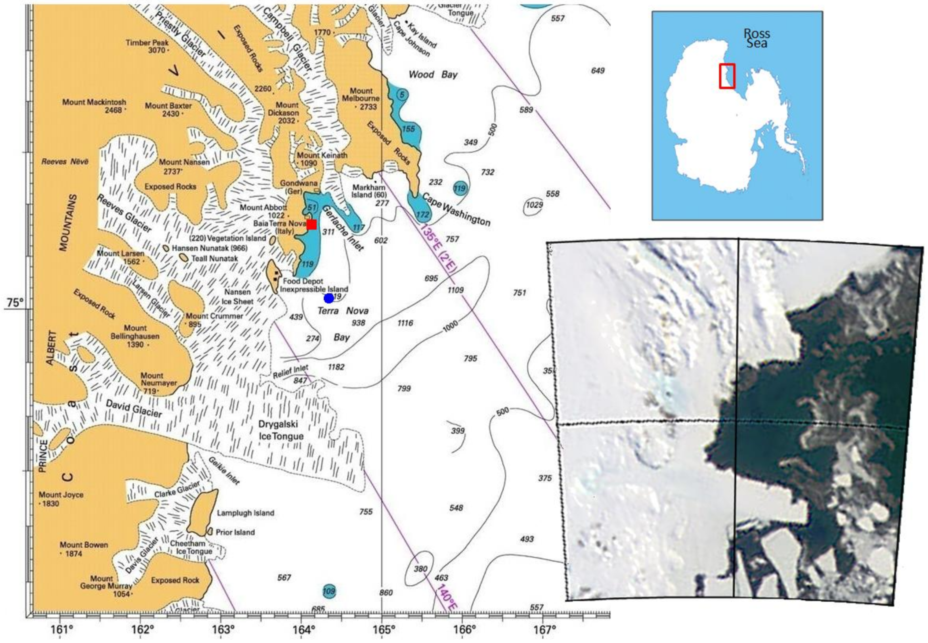

Figure 1. Map of the study area. Dot and square correspond to the position of the D2 mooring and the Antarctic Weather Station ENEIDE, respectively. Satellite image taken on 26 December 2001, provided by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project from NASA, shows the Drygalski Ice Tongue and evidences the polynya area.

Two Aanderaa RCM7 eulerian current meters were also mounted on the same mooring, at 89 m and 179 m depth 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, 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 depth, respectively.

During the deployment and recovery of the moorings, CTD casts were carried out and 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 meteorological station on land closest to the experimental area at sea. Since direct solar radiation measurements were available only from early November to mid-February, the theoretical no-sky solar radiation was computed by MatLab$^{@}$ air-sea toolbox version 2.0:8/9/99. This parameter is used to infer the seasonal and daily cycle of irradiance and ranges between 0 and 884W/m^2 at the latitude of the mooring. Sea ice concentration data at 25 km resolution in the area bounded by 164° E and 165.5° E and 74.5° S and 75.5° S were obtained from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) and the Defence Meteorological Satellite Program (DMPS, USA) SSM/I passive microwave analysis archived at the National Snow and Ice Data Centre (Cavalieri et al., 2008).

2.2 Environmental conditions during the experiment

Sea-ice coverage satellite data allowed a rough estimate of the temporal evolution of the Terra Nova Bay polynya extension and, consequently, to determine when the sea surface on the mooring location was free from sea-ice. The temporal series of sea-ice concentration data extracted in the closest pixel to the position of the mooring evidenced that the ice never completely covered the area throughout the period of the measurements. The largest sea ice coverage occurred from June to October, while during February it was below 20%. The strong katabatic westerly winds associated to an increase of the air temperature supported a large polynya area. Conversely, after periods of low wind, the sea ice concentration underwent to a relative expansion, as occurred during the second half of May and during mid-March.

Sea currents were mainly barotropic, directed towards Northeast with a mean speed of about 30 cm/s, (Cappelletti et al., 2010). From February to April, they had a lower speed and were eastward. In the upper 16 m, the horizontal currents were strongly wind driven reaching hourly mean velocity of about 70 cm/s.

In this surface layer, the vertical velocities were very strong with peaks up to 20 cm/s and showed a high variability, particularly on December, when, notwithstanding low wind intensity, the vertical motions were intensified by thermohaline forcing due to early ice melting.

At deeper depths, along the whole water column, the greatest vertical velocities occurred 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.

The sea temperature and salinity time series available at the depth of 126 m showed some episodes of ice melted waters mixing even at this depth. The salinity reached the minimum (34.54 psu) only at the end of May, while the maximum (34.76 psu) occurred on October. The sea water temperature was constant at -1.92 °C from late March to the end of November. As the results of the ice melting, summer CTD casts evidenced a surface layer with salinity lower than 34 psu and slightly warmer waters just above the zero degree that helped to enhance the generally weak vertical stratification. During winter, uniform temperature close to the freezing point, strong mixing and dense water formation processes made the water column vertically instable.

At this latitude, the polar night lasts from 29 April to 11 August and the midnight sun period is from 3 November to 8 February.

2.3 ADCP Data quality check

Detailed analysis on the data quality check performed on the ADCP data can be found in Cappelletti et al., 2010. In particular, pitch, roll and tilt angles data were all below the limits provided by the manufacturer. This assured that the mooring maintained the vertical position despite the strong currents in the region. In addition, the so-called "percent of good data", confirmed the high quality of the collected measurements. A further quality check to detect outliers, gross errors, and not coherent data was done on echo intensity data before computing the backscatter strength (Sv). Specifically, it was verified that each measurement fulfilled the following condition to obtain a good signal to noise ratio:

$$K_c*(E-E_{noise})>10$$

where E_{noise} is defined as the minimum recorded raw value in the experiment (in the present case 55 counts), E is the raw echo intensity and K_c is the conversion factor for echo intensity in count to dB. All observations not satisfying the above condition were discarded.

Some other tests have ruled out any noise on the data due to the presence of the eulerian currentmeter that was located on the same mooring at 86 m depth.

The mean profiles of echo intensity data for each beam signal usually shows a decrease with the increase of the distance from the source. Furthermore, the air-sea interface strongly affects the closest bins to the sea surface. Therefore, as suggested by the manufacturer, data from the bin located at the air-sea interface were discarded.

2.4 Backscatter strength computation

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

Echo intensity amplitude depends on the instrument's technical characteristics and on the sampling setting. The formula returns absolute physical data (backscatter strength), thus allowing the comparison among different data set (Fielding et al., 2004).

Due to the lack of the concurrent profiles of temperature and salinity 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. Constant values were adopted after checking the low impact of temperature and salinity variability on the computation of these parameters.

In the period of measurements, the temperature variation in the upper layer was limited to few degrees, while that of the salinity is less than 1 psu. These variations affected the computation of the sound speed just in the upper 50 m and only during the short melting period. 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 psu, pH=8, z=80 m. As in the previous case, the limited range of variability of these parameters has a small influence on the value of the coefficient. In fact, 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 further 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 that one 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.

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

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

where

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

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

α=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 = 2 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 echo 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 behaviour. The method proved to be useful also for analyzing meteorological and oceanographic data (Soares and Cherneva, 2005). It was successfully applied to a long-term ADCP backscatter observations for the study of the zooplankton migration characterized by a strong daily and/or sub-daily variability (Bozzano et al., 2014).

Time frequency analysis of acquired backscatter strength data was performed on 240 h-long samples selected with a centred window moving at 24 h step. Ten days interval is 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.

Backscatter signal due to zooplankton migration can be assumed as a 24 h period square-wave like form. The contribution of the twilight migration, typical of some 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. However, in the case of the polar regions, the length 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. As consequence, secondary peaks on both even and odd harmonics would characterize the resulting spectrum and this could mask the contribution to the backscatter related to the twilight migration pattern of the zooplankton. By way of example, the following three cases are shown. In the first case, the signal is a symmetric 24 h period square wave (duty cycle 50%). In the second one, it is an asymmetric 24 h period square wave (duty cycle 62%), while in the third case is the sum of two symmetric square waves (duty cycle 50%), one having 24 h period and the other one a 12 h period with a 30% reduction of the amplitude and 6 h phase shift. Random noise having an amplitude of one tenth of the 24 h square wave amplitude is added in all three cases (Figure 2 left). Then FFT analysis is performed on the three samples (Figure 2 right). A 12 h peak appears in the FFT spectrum of second case. This is just due to the effect of the 62% duty cycle of the original 24 h square wave and it is greater than the peak of the third case, which, on the contrary, results from the real presence of a 12 h component in the analyzed signal.

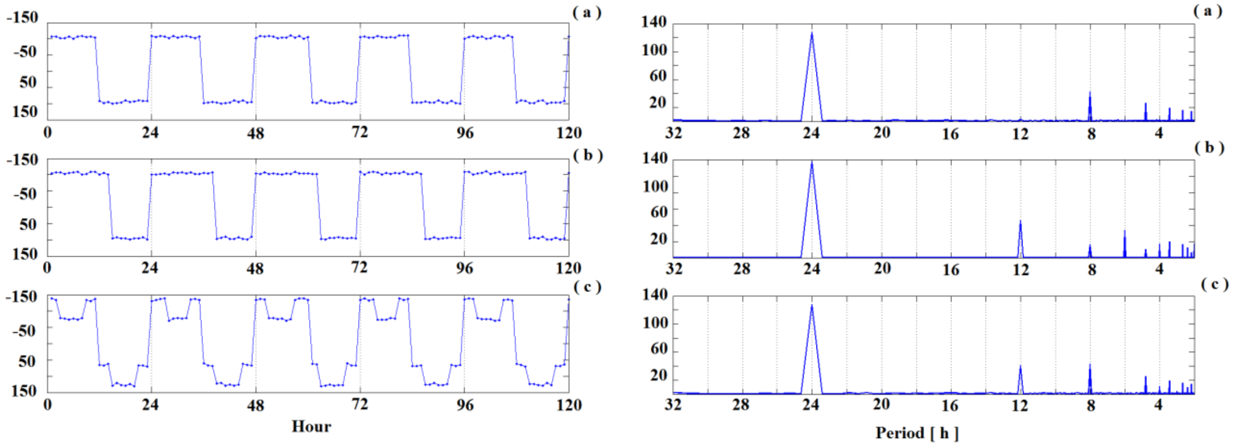

Figure 2. Simulated signal and relative FFT spectrum for the three cases: a) 24 h period square wave with duty cycle=0.5; b) 24 h period square wave with duty cycle=0.62; c) sum of 24 h and 12 h period square waves with duty cycle=0.5.

Therefore, the interpretation of the results may be ambiguous and requires particular attention. In order to avoid misleading interpretation of the data, it is necessary to perform a careful analysis of the spectrogram of the 12 h signal, also in comparison with the correspondent obtained for the 24 h, identifying the periods when the signal is significant and, if necessary, with the help of a visual inspection of each selected period.

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. Thus, the time series of daily average backscatter strength profiles (Figure 3) is firstly analyzed in order to identify possible causes influencing the backscatter intensity.

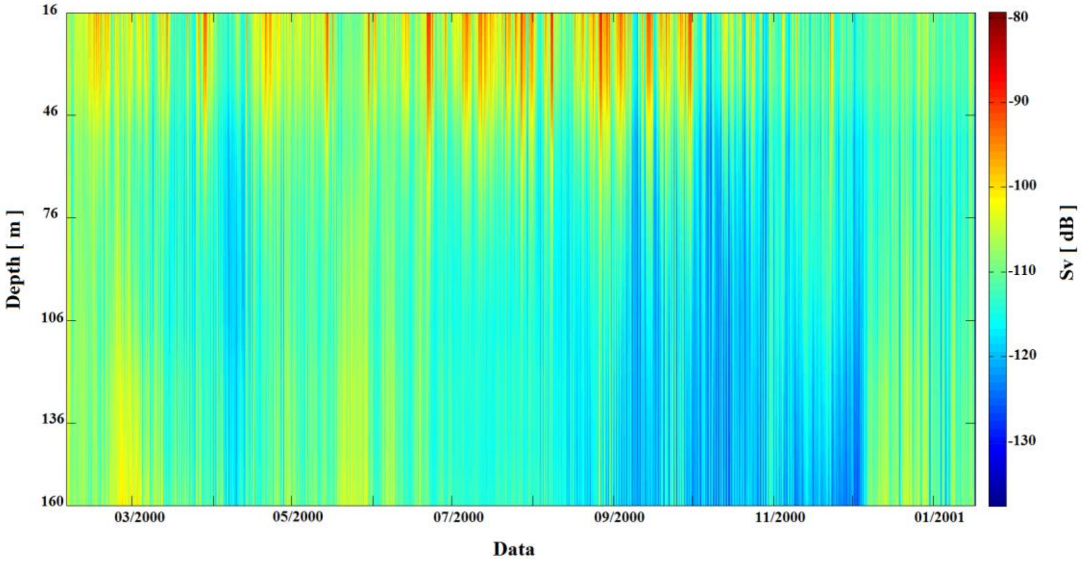

Figure 3.Temporal variability of the acoustic backscatter strength during the entire period of measurements.

The results of the correlation analysis between the data collected in the ten layers (Table 1) showed that the features in the upper 72 m meter of the water column differ from those in the layer between 104-168 m depth.

Depth limits of each bin [m]	152-168	136-152	120-136	104-120	88-104	72-88	56-72	40-56	24-40	8-24
Bin Bin	1	2	3	4	5	6	7	8	9	10
1	1	0.94	0.87	0.73	0.6	0.49	0.26	0.52	-0.04	-0.12
2		1	0.97	0.86	0.72	0.57	0.28	0.03	-0.09	-0.13
3			1	0.95	0.85	0.70	0.38	0.08	-0.08	-0.10
4				1	0.96	0.82	0.51	0.14	-0.05	-0.07

5					1	0.93	0.64	0.27	0.03	0.02
6						1	0.86	0.53	0.28	0.26
7							1	0.86	0.67	0.61
8								1	0.93	0.86
9									1	0.92
10										1

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

Higher variability and greater values occurred 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 4).

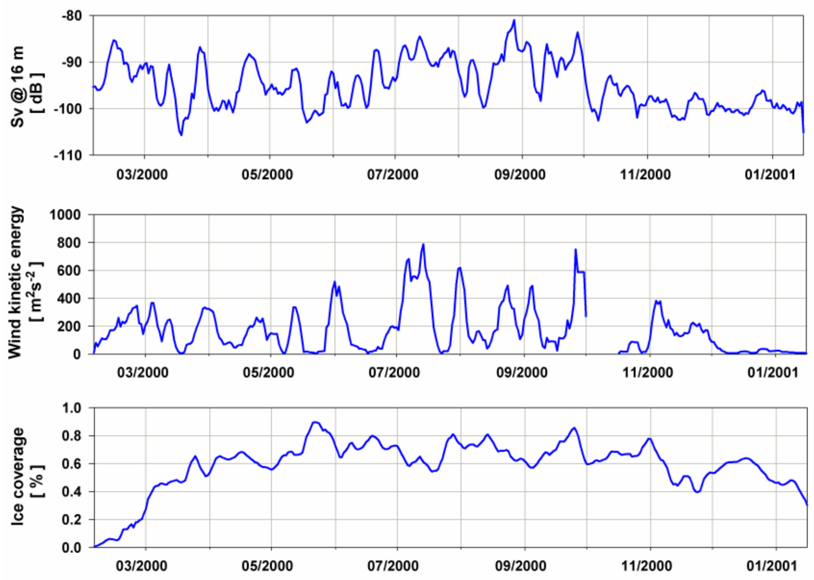

Figure 4. Time series of daily observations of backscatter strength at 16 m depth, wind kinetic energy and sea ice coverage during the whole measurements period.

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. High values also occurred during the last two weeks of May, following a period characterized by very low backscatter intensity.

Low values are more frequent in April and from September to late November. Relative minima are common to all layers in many periods.

To focus on sub-daily variability, spectral analysis was performed on the whole series of hourly mean backscatter for each level on 34 adjacent subsample of 240 h and then averaged to increase the confidence level (Figure 5). 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 the 12 h and a series of peaks on the higher harmonics.

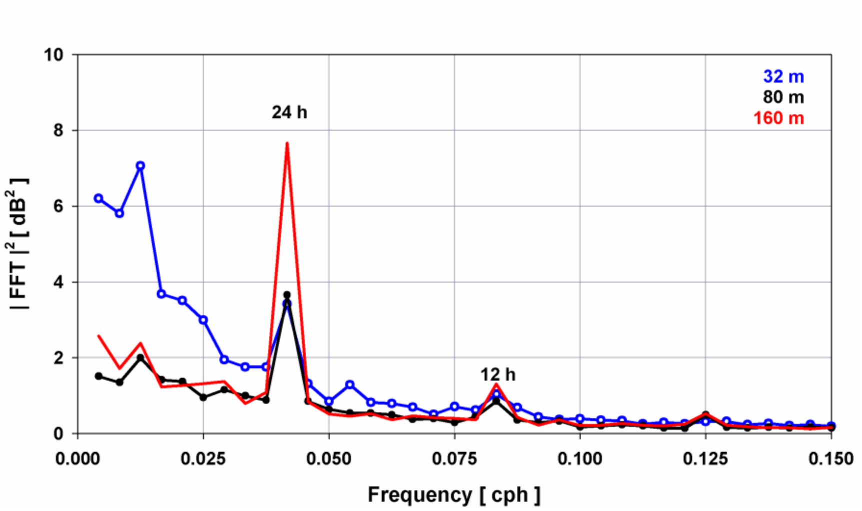

Figure 5. Power spectrum of the backscatter strength at 32 m (solid line, empty dot), 80 m (solid line, full dot) and 160 m (solid line) depth as the average of the FFT performed on 34 adjacent subsamples 240 h (ten days) long.

In order to evaluate the temporal evolution of the two main evidenced harmonics, time frequency analysis was performed as described in Section 2.5. For each depth, the amplitude of the 24 h and the 12 h harmonics were extracted from the respective spectrum, obtaining the temporal series of the two amplitudes. The vertically integrated time series of the amplitudes, superimposed to the computed solar cycle and the moon phase, are shown in Figure 6 and well evidence the main features of the migratory phases of zooplankton in the area.

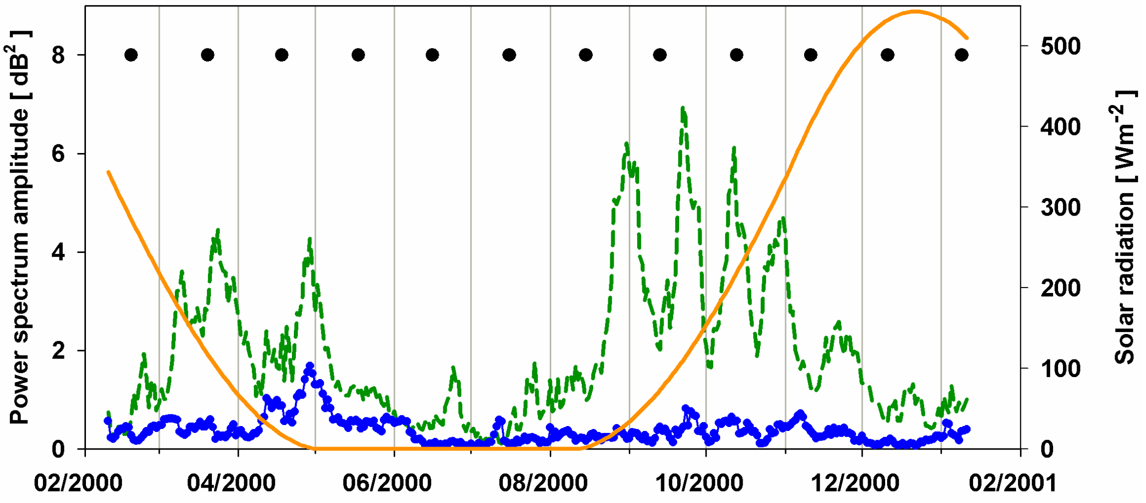

Figure 6. Temporal evolution of no-sky solar radiation (solid line) and the vertically integrated (from 8 to 176 m depth) amplitude of the 24 h (dashed line) and the 12 h (dotted line) harmonics. Black dots represent the full moon on the mooring site.

Four major episodes characterized the presence of zooplankton seasonal migratory patterns. The first one occurred at the end of August and lasted about ten days, the others approximately every three weeks, the last being at the end of October. Vertical daily migration was 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 was quite low even in correspondence of the highest 24 h peaks. The main peak was at the end of April in correspondence of a relative maximum of the 24 h amplitude time series.

The analysis of the spectrograms (Figure 7) 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 reached the values of 0.7 with the adjacent levels at 80 m depth and 48 m.

Whereas the major four 24 h peaks dominated in the lower layers, the signal around 80 m depth had 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 occurred also between March and June, with the most significant centred at the beginning of May.

The amplitude of the 12 h harmonic was generally lower and had different temporal evolution. Twilight migration seemed prevailing on April and May and at intermediate depths, between 64 and 112 m. Some 12 h peaks of particular importance occurred on May at 80 m depth and on mid November at the deepest level.

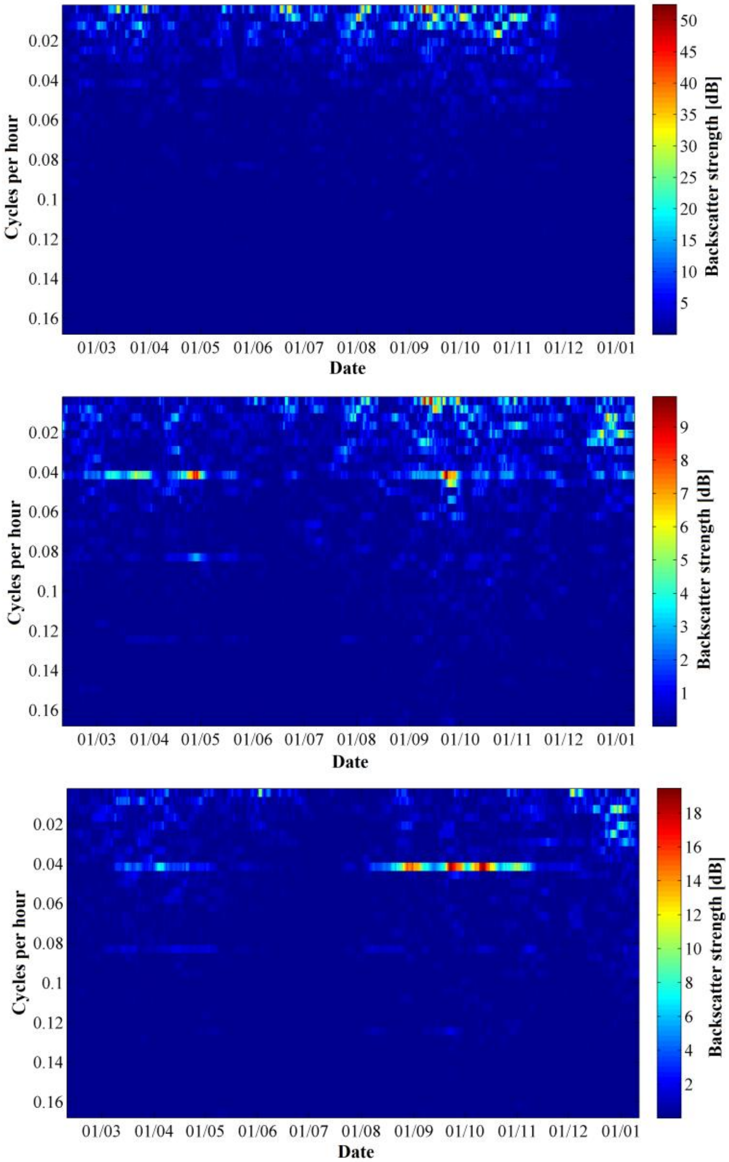

Figure 7. Spectrograms of backscatter data at (top) 32 m, (middle) 80 m and (bottom) 160 m depth.

3.2 Migratory patterns

To better characterize the annual migration patterns, the analysis was performed on several sub-sets of hourly backscatter strength data corresponding to the most evident 24 h and 12 h peaks of the spectrogram at the depths of 160, 80 and 32 m, representative of deep, intermediate and surface layers, respectively. All sub-sets were smoothed by using a centred three hours moving average for reducing the high frequency variations and the noise.

During the first examined period, at the end of the polar night, backscatter signal at 160 m (Figure 8a) evidenced the strong link between the daily variability and the solar cycle. In this period, the nights lasted from 18 to 14 hours and the solar radiation was quite low. Absolute minima of backscatter signal at 160 m depth exactly occurred in correspondence with the short daily light maximum and all had similar values. During the night, the cycles were more different from each other: the value of the maximum varied while the relative minimum, indicating the twilight migrations, sometimes was very well marked, sometimes hardly appeared. In the upper layers, a daily cycle was clearly identified only at the end of the examined set, when the time evolution of the backscatter signal was similar at all depths suggesting an upward migration that affected the entire water column monitored by the ADCP.

In the second week of September, the absolute minima, when present, tended to anticipate the maximum of solar radiation.

Three weeks later (Figure 8b) the nights became shorter, lasting from 10 hours to only 5 at the end of this second examined period while the solar radiation started to significantly increases. Again, there was a very good correspondence between absolute minima of the backscatter signal at 160 m depth and maxima of the no-sky solar radiation. However, in this sub-set the diurnal relative maxima were more evident and the nocturnal relative minima were generally smoother than in the previous examined period. On the contrary, at the intermediate depth, the backscatter strength did not show a well marked diurnal cycle indicating that zooplankton tended to remain stable near the surface.

The third selected sub-set (Figure 8c) lasted from November 11 to December 1, during the austral summer period, and it was in correspondence with the period of maximum intensity of the 24 h harmonic in the upper level, as resulted by the time frequency analysis. In this period the solar irradiance reached its maximum values and there was light also during the night. Although the daily cycle in the upper layer was more evident in this period and its amplitude was comparable with that of the deeper level in spring, the signal was never so clear. On the contrary, during this period the daily cycle signal in the deeper level showed a reduced amplitude and it was not well marked, as it also resulted by the time frequency analysis.

During the autumn season (Figure 8d) a clear semidiurnal cycle was present in the backscatter strength of intermediate and deep layers and it was prevailing over that of the 24 h. This might be due to a limited food concentration as the observations made by Godlewska (1996) suggest.

In winter (Figure 8e), no migratory pattern was evidenced, but in the intermediate and surface levels the signal showed a variability that might be ascribed to the presence of larvae dwell near ice edge (Daly, 1990).

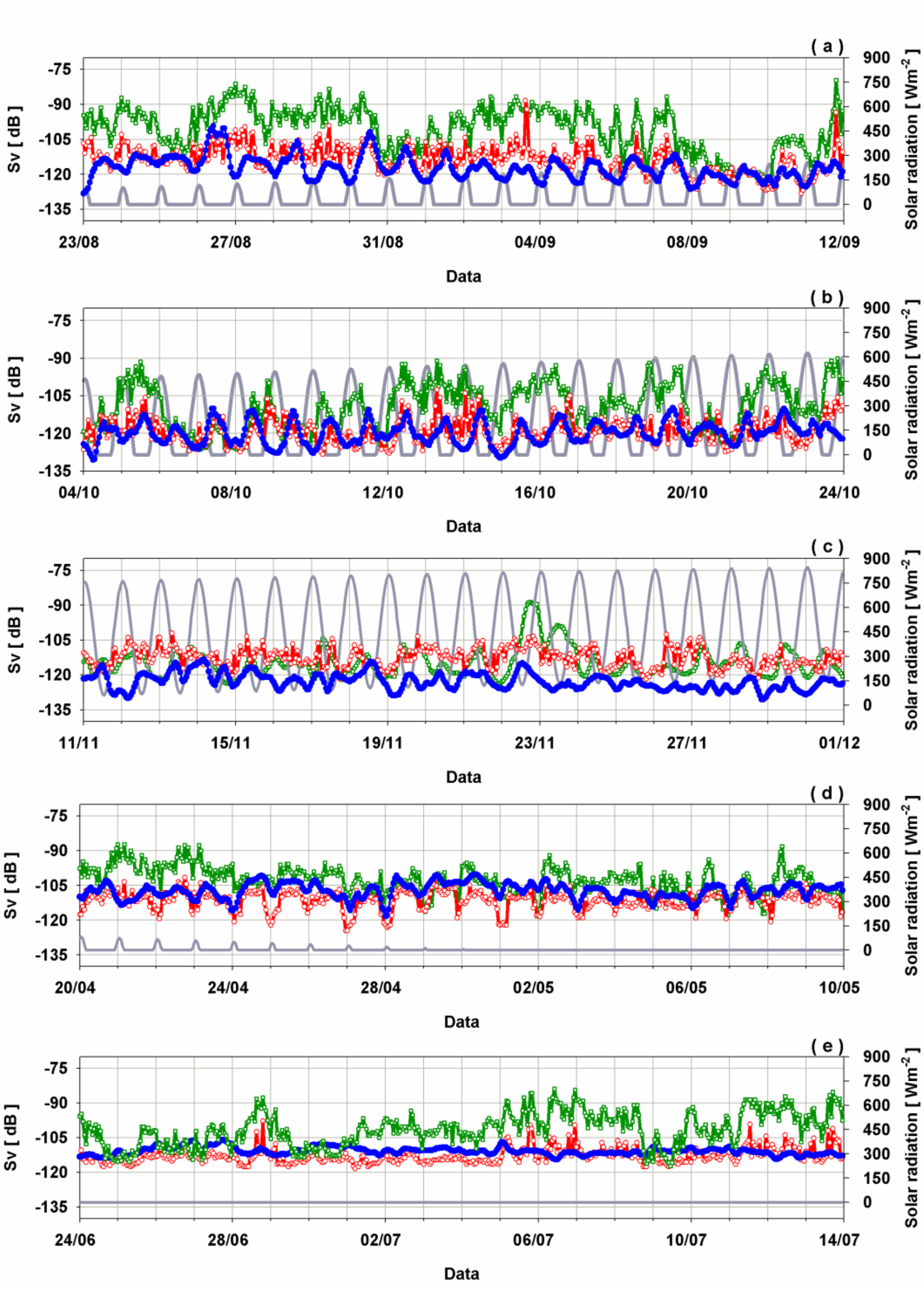

Figure 8. Time series of 20 days sub-samples of backscatter strength at 160 m (full dotted line), 80 m (empty dotted line) and 32 m (empty square line) depth superimposed to the temporal evolution of no-sky solar radiation (solid line).

3.3 Diel variability

The analysis of the migratory phases of zooplankton shows the strong relationship with the variation in the duration of daytime. However, even the differences in light intensity might be regarded among the causes of the 24 h upward and downward movements.

In order to investigate the diel variability, the same sub-sets of data selected in the previous Section are used with the exception of the one corresponding to the midnight sun period. For each of them, the hourly mean values of Sv have been computed.

The diel variability was well detectable comparing the averaged Sv to the time of sunset and sunrise: zooplankton moved towards the surface at the sunset and vice versa near the sunrise in all periods in which the sun alternation occurred at the mooring site.

From the end of August to the middle of September (Figure 9a) sunset and sunrise occurred between 4:11 to 6:17 UTC and between 21:54 and 19:37 UTC, respectively. The diel cycle was well marked in the deepest layer where the most relevant upward movement was in correspondence with sunset and the downward movement with the sunrise. Sv at 80 m and 32 m depth showed 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 was similar to the sunlight cycle with night-time lasting about 13 hours.

In the following month (Figure 9b) night-time decreased, sunset occurred from 8:13 to 10:36 UTC and sunrise spanned from 17:27 to 14:56 UTC. The curve corresponding to diel variability at 160 m depth had the same Gaussian shape of the previous period, but it was narrower and again the most sharp movement upward and downward occurred near sunset and sunrise, respectively. Sv at 80 and 32 m depth showed lower values than in September, but a more marked diel cycle. Only during night-time, backscatter strength at intermediate depth was higher than one at the deepest level.

One month after the March equinox (Figure 9c), it was 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 three selected depths showed 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 were lower for all analyzed periods with respect to the deepest level and showed the most wide diel cycle.

During austral winter, when no sun light was present (Figure 9d), no migration occurred. The backscatter strength at each level was quite constant with very small variations, apart from some movements in the upper level that might be ascribed to the presence of larvae.

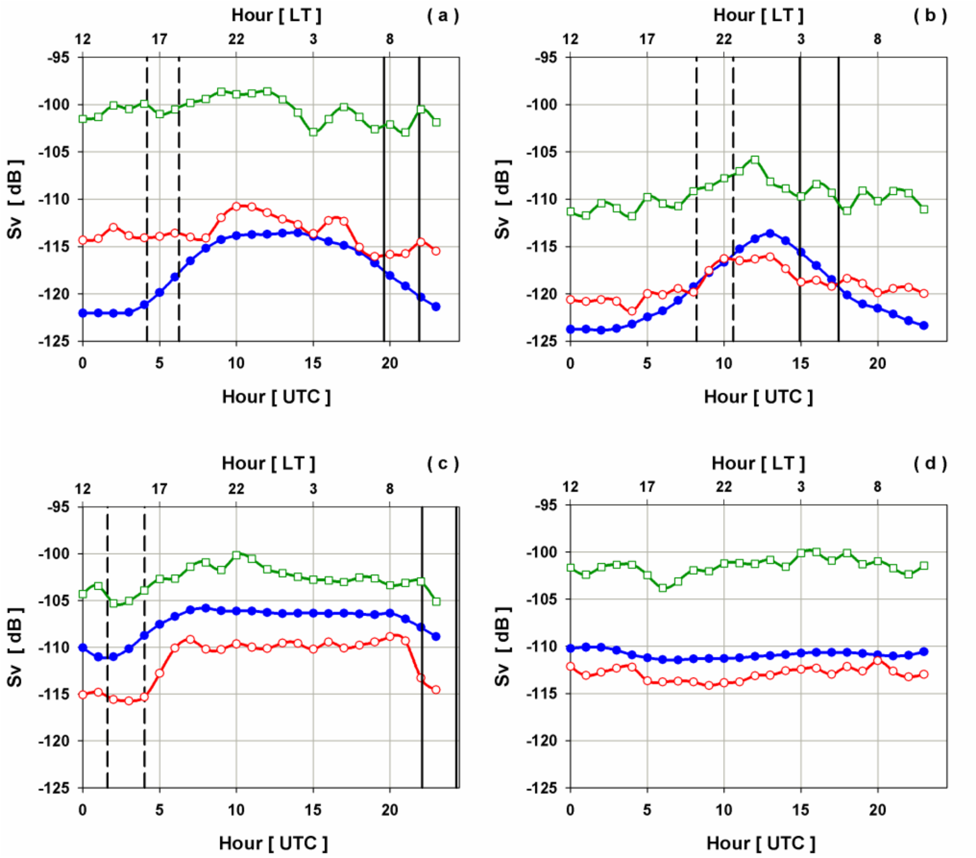

Figure 9. Averaged diel cycles at 160 m (full dotted line), 80 m (empty dotted line) and 32 m (empty square line) depth for the following periods: a) 23/8 -12/9; b) 4/10-24/10; c) 20/4-10/5; d) 24/6-14/7. Vertical lines indicate sunset (dashed line) and sunrise (solid line) at the beginning and the end of each period. Hours are expressed in UTC time and in local time (LT = UTC+12) on lower and upper horizontal axis, respectively.

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 176 m was re-analyzed with the aim to investigate the zooplankton migrations.

This ADCP data was originally collected for a completely different purpose. As a consequence, the sampling time (1 hour) was lower than the one generally necessary for this type of application, but it was suitable for performing an accurate spectral analysis. Although the ADCP was working at 150 kHz, this frequency was quite appropriate to address the study of macro-zooplankton and krill which represent an important part of the Antarctic zooplankton. Thus, the use of time frequency analysis allowed extracting useful information about the zooplankton dynamics in the area during one entire year.

Assuming that the periodicity of the backscatter signal at 24 h and 12 h periods was related to the diel vertical migration, some information on the seasonal cycle of zooplankton were achieved from the analysis of the temporal evolution of the amplitudes time series obtained by the FFT analysis.

Signal ascribed to the daily migration generally dominated in the examined time series and reached great values. Significant differences resulted between the upper and deeper examined layers, both in terms of presence and migration pattern. In the deeper layers, the daily signal was prevailing, but the presence of sub-daily migration pattern was quite often detected.

Furthermore, the 24 h and the 12 h signals had a high amplitude even when the measured backscatter data were low, such as during September and October. This didn't occur during December and January, when the backscatter data reached their maximum values.

The analysis did not reveal any relation between the backscatter patterns and the dynamic of the area where a passage of different water masses was not detected and the observed small temperature and salinity variability was mainly due to winter dense water formation and summer ice melting. Furthermore, the high vertical dynamics and the low temporal and spatial resolution of the measurements masked any possible correlation between backscatter signals and vertical velocities.

On the contrary, a good correlation between the solar annual cycle and migration pattern was common to all examined depths while no evident relation between the time series of the 24 h and the 12 h period amplitudes and the full moon phases was found. Additionally, a clear link between the ascending/descending movement and the sunset/sunrise was evidenced.

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

Daily migration initiated in the late August, just after the end of the polar night, reached the maximum at the beginning of September and then decayed. Other three periods of intense migration, each lasting about ten days, followed this first period of intense motion until mid-November. Unlike to what happens in the ice-covered areas around, in the polynya the sun light immediately penetrates in the water. This explains the early occurrence of the first observed peak.

Since the ADCP measurements were not calibrated with in-situ net catches, it was not possible to detect in a unambiguous way zooplankton taxa but only to infer the presence of some species analyzing the relation between the patterns and the season, the hour of sunset/sunrise or the daylight length, taking into account what is already known about their behaviour.

From the half of February to the first days of April 2000, the time series of the 24 h period amplitudes showed an intense migratory phase that might be due to the presence of the Ice krill *Euphausia crystallorophias*. This hypothesis is supported by the analysis carried out by Sala et al. (2002). They, during a survey carried out in the Ross Sea between January and February 2000, found a high concentration of *Euphausia crystallorophias* in the shelf water and coastal stations close to the mooring site. They suggested that the overall length frequency distribution of *Euphausia crystallorophias* was characterized by a first mode of juvenile individuals and a second mode consisting of sub-adults and adults that perform diel vertical migration.

Euphausia crystallorophias is a swarming species and this could explain the observed elevate values of backscatter strength in the first months of the deployment along the whole water column characterized by a diel (24 h and 12 h) vertical migration. During austral winter, the greatest values were collected near the surface, where it is believed that *Euphausia crystallorophias* complete its larval development since sea-ice edge is a natural nursery habitat (Brierley and Thomas, 2002).

Although many species of Antarctic zooplankton remain active also in winter, they limit their vertical migration keeping a state of quite metabolic depression (Nicol, 2006) or descending to the seabed that is rich of organic matters to feed themselves (Smith and Demanster, 2008). This behaviour could be reflected in the simultaneous acquisitions of great backscatter values and almost absent migratory signal.

The low backscatter values observed in the first half of April and during spring may be associated to the scatter provided by the presence of copepods, as the *Calanoides acutus*. The life cycle of these copepods consists in a descent to deepest level in correspondence to an increasing of the sea-ice concentration, a diapause period during winter below 500 m depth and an intense migratory phase in spring, when ice melting occurs (Schnack-Schiel et al., 2008).

The rapid interchange between low and high backscatter strength values occurred in early December migth be due to a variation in the zooplankton populations subsequent to phytoplankton blooms, which in Terra Nova Bay generally occurs twice, the first time between December and January and the second in February (Innamorati et al., 2000).

In-situ measurements of mesozooplankton biomass performed in December and January by Hernández-León et al. (1999, 2000) revealed a low presence of copepods and a high concentration of krill, confirming the inverse relation between krill and non krill species pointed out by several authors (Hosie, 1994; Voronina et al.,1994).

In December and January, the change of the Sv values corresponded to an opposite trend of the migratory signal. Similar results were found in the Lazarev Sea by Cisewski et al., (2010). They ascribed the strong reduction of migration to a decreasing of the zooplankton population in the examined water column or to the limited difference in the daily solar radiation cycle. A further hypothesis to explain the absence of diel cycle was proposed by Cottier et al. (2006). They ascribed this absence to a chaotic up and down motion of the zooplankton for both feeding and escaping from predators.

The observed relation between acoustic backscatter strength and migratory pattern was limited only to the upper 176 m of the water column. Although the major density of euphausiid and copepods population reside in the surface layers during spring and summer months, it was not possible to investigate change in density as depth increases or possible descent of zooplankton to the sea floor owing to the mooring configuration. This limit affects the measurements in the winter months also. As a consequence, the hypothesis of diapause of copepods is only based on their general behaviour.

The carried out analysis of a long time series of backscatter data performed in the time frequency domain allowed identifying in automated and objective way signals for the investigation of zooplankton migrations. The method of analysis is simple but efficient to extract precious information even from signals that may have poor spatial and temporal resolution. This implies that the already available long-term acoustics data, even if obtained from non-dedicated, low-resolution measurements, could provide additional time series of relevant biological data giving a significant input to ecosystem dynamics and productivity studies. They are of particular interest in the polar regions where direct observations are scarce and difficult to be obtained. Hence, it should be valuable to include ADCP in existing environmental observing systems.

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Depth limits of each bin [m]	**152-168**	**136-152**	**120-136**	**104-120**	**88-104**	**72-88**	**56-72**	**40-56**	**24-40**	**8-24**
Bin \ **Bin**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1	0.94	0.87	0.73	0.6	0.49	0.26	0.52	-0.04	-0.12
2		1	0.97	0.86	0.72	0.57	0.28	0.03	-0.09	-0.13
3			1	0.95	0.85	0.70	0.38	0.08	-0.08	-0.10
4				1	0.96	0.82	0.51	0.14	-0.05	-0.07
5					1	0.93	0.64	0.27	0.03	0.02
6						1	0.86	0.53	0.28	0.26
7							1	0.86	0.67	0.61
8								1	0.93	0.86
9									1	0.92
10										1

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

Figure_1

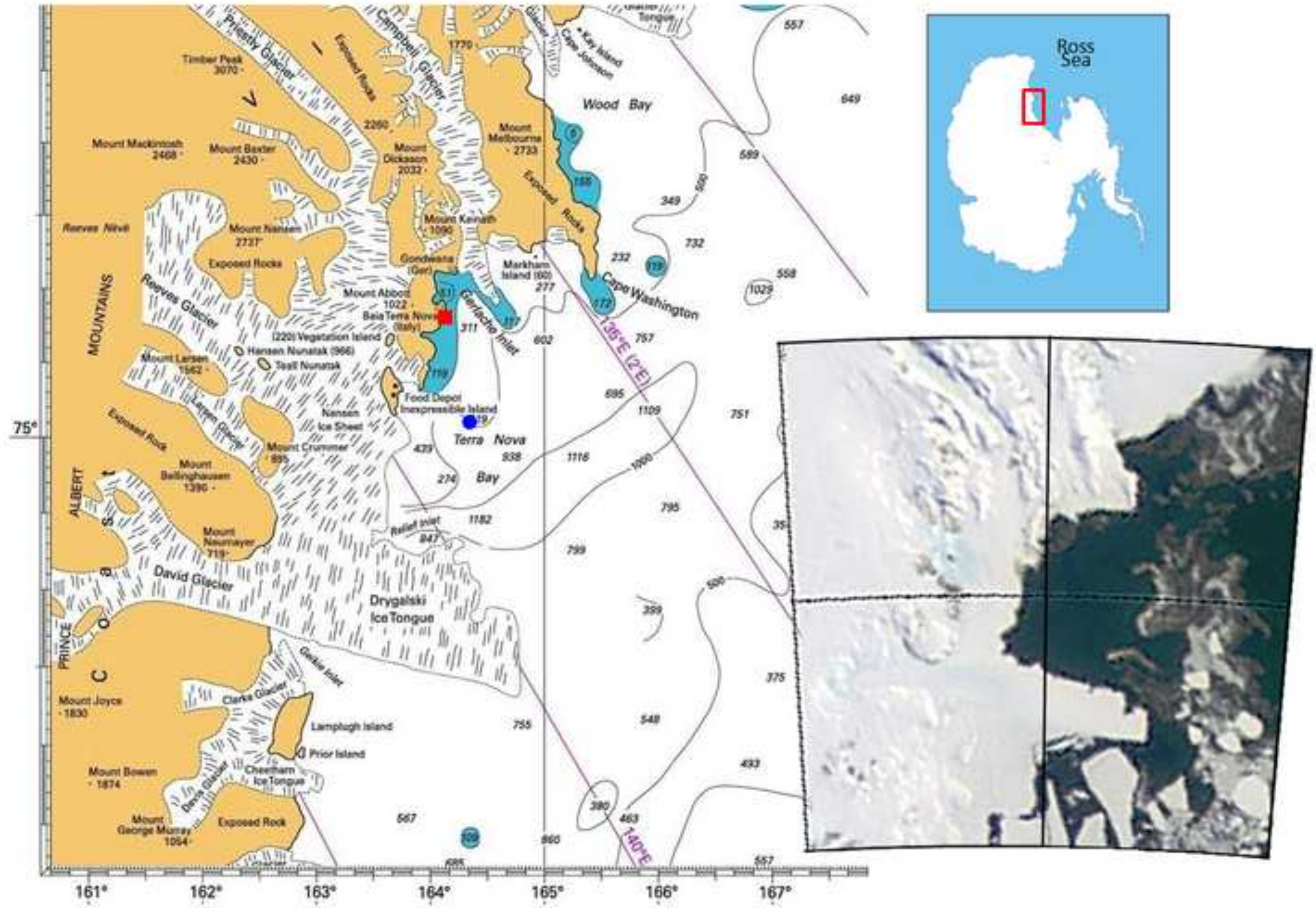
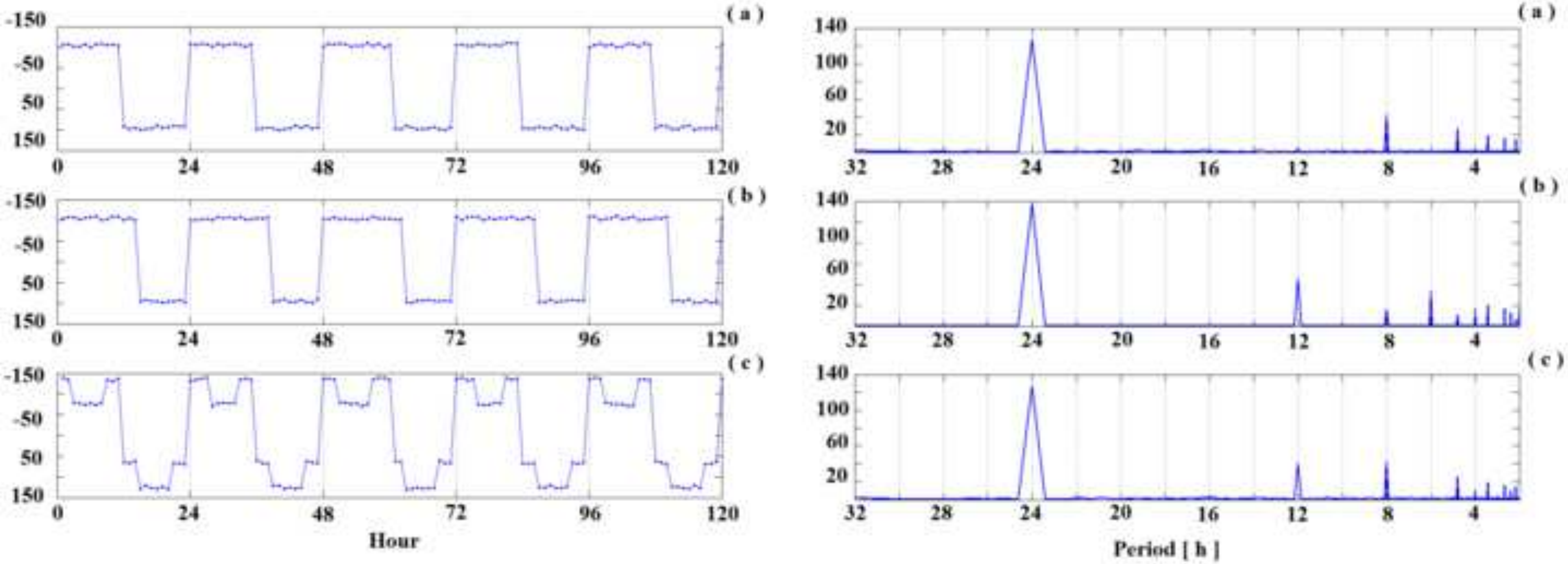

Ross Sea
Priestly Glacier
Campbell Glacier
Timber Peak 3070
Exposed Rocks
Mount Mackintosh 2468
Mount Baxter 2430
Mount Dickason 2032
Mount Melbourne 2733
Wood Bay
Cape Johnson
Kay Island
Reeves Névé
Mount Nansen 2737
Mount Keinath 1990
Gondwana (Ger)
Markham Island (60)
Mount Abbott 1022
Baia Terra Nova (Italy)
Gerlache Inlet
Cape Washington
Reeves Glacier
(220) Vegetation Island
Hansen Nunatak (966)
Teall Nunatak
Mount Larsen 1562
Larsen Glacier
Food Depot
Inexpressible Island
Nansen Ice Sheet
Mount Crummer 895
Terra Nova Bay
Exposed Rock
Mount Bellinghausen 1390
Mount Neumayer 719
Relief Inlet
David Glacier
Drygalski Ice Tongue
ALBERT MOUNTAINS
PRINCE
Mount Joyce 1830
Geikie Inlet
Clarke Glacier
Lamplugh Island
Prior Island
Mount Bowen 1874
Cheetham Ice Tongue
Davis Glacier
Mount George Murray 1054
135°E (2°E)
140°E
75°
161°
162°
163°
164°
165°
166°
167°

Figure_2


(a)
-150
-50
50
150
0
24
48
72
96
120
(b)
-150
-50
50
150
0
24
48
72
96
120
(c)
-150
-50
50
150
0
24
48
72
96
120
Hour
(a)
140
100
60
20
32
28
24
20
16
12
8
4
(b)
140
100
60
20
32
28
24
20
16
12
8
4
(c)
140
100
60
20
32
28
24
20
16
12
8
4
Period [h]

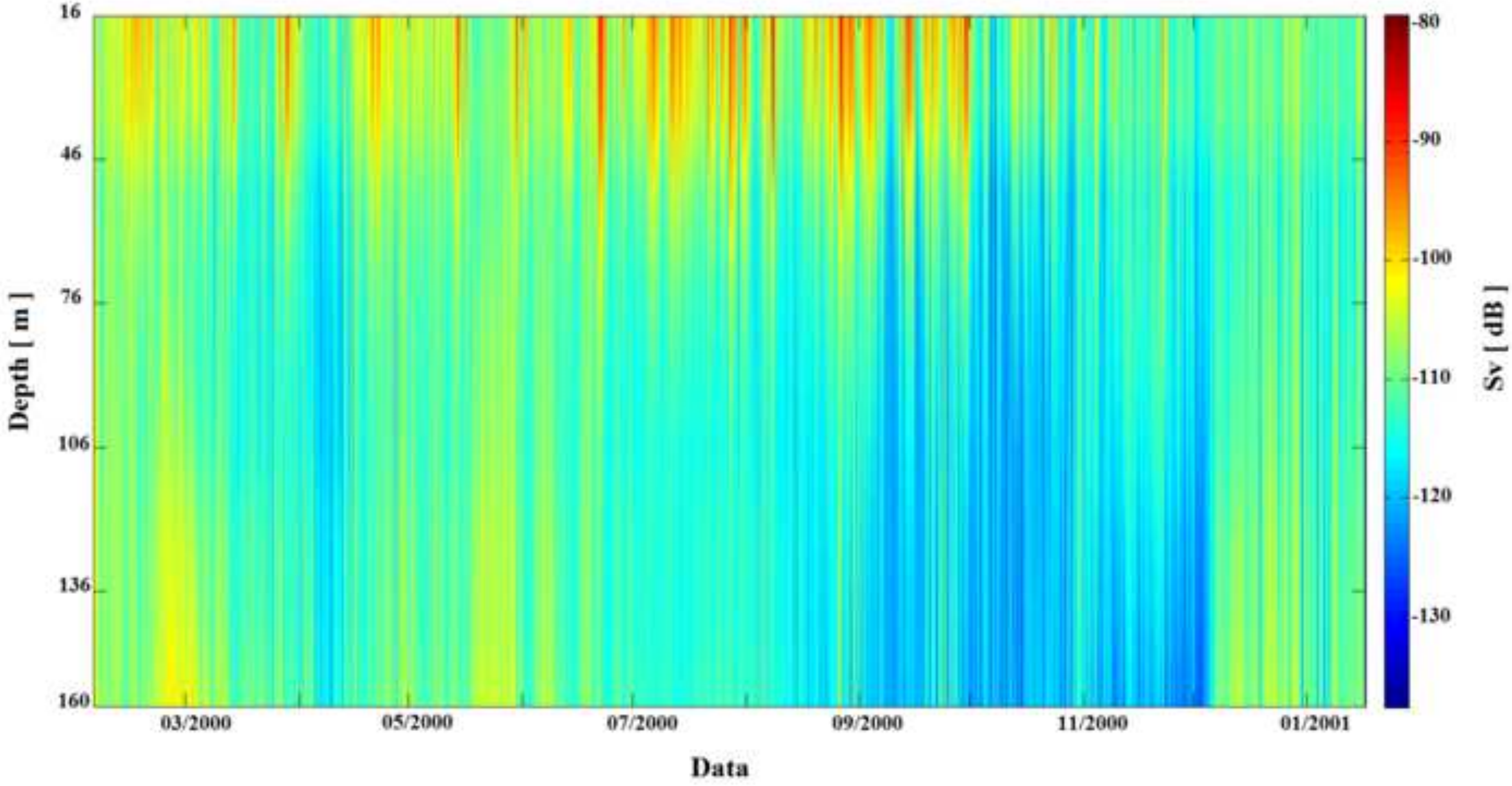

16
46
76
106
136
160
Depth [m]
03/2000
05/2000
07/2000
09/2000
11/2000
01/2001
Data
-80
-90
-100
-110
-120
-130
Sv [dB]

Figure_4
Click here to download high resolution image

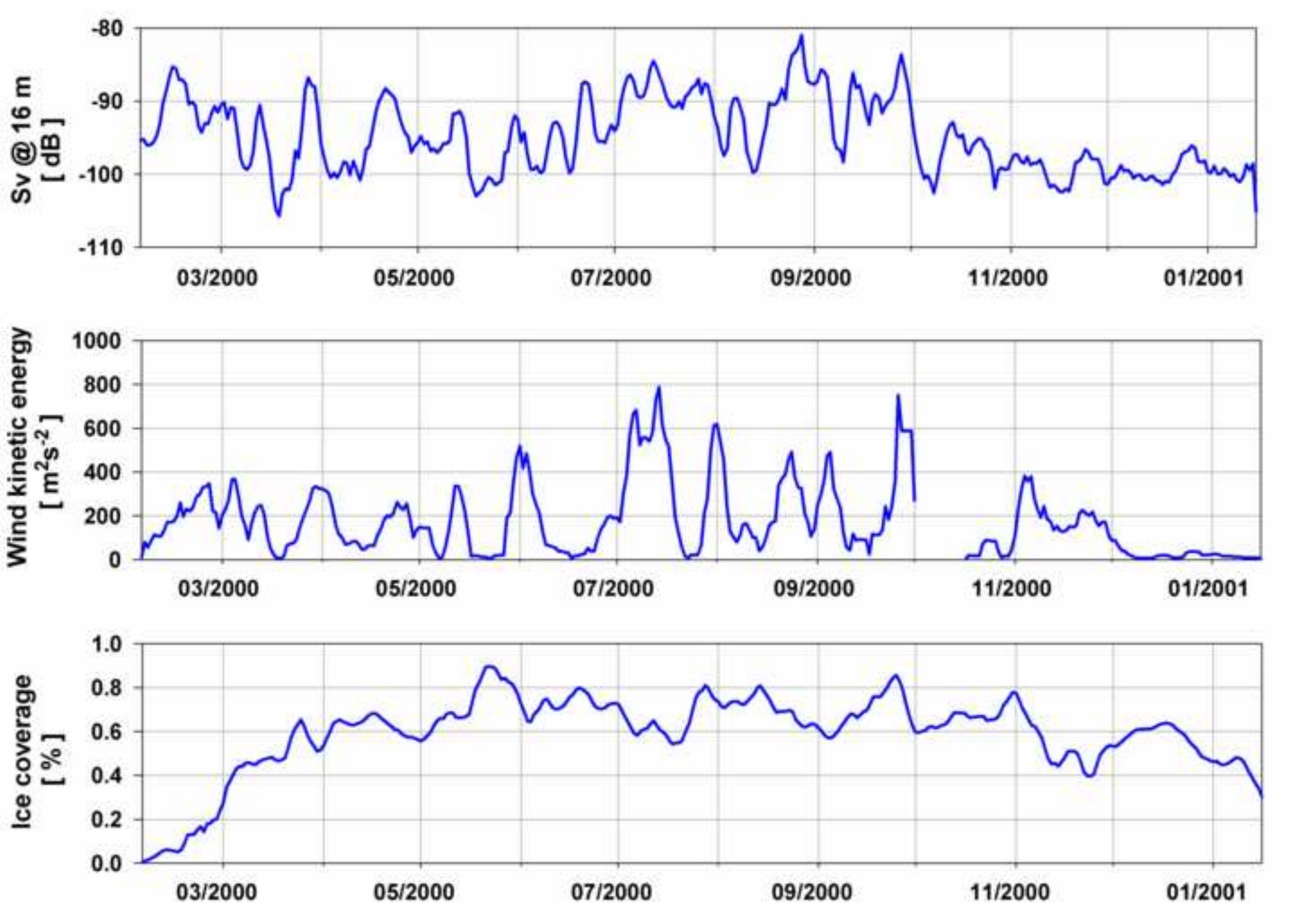


Figure_5

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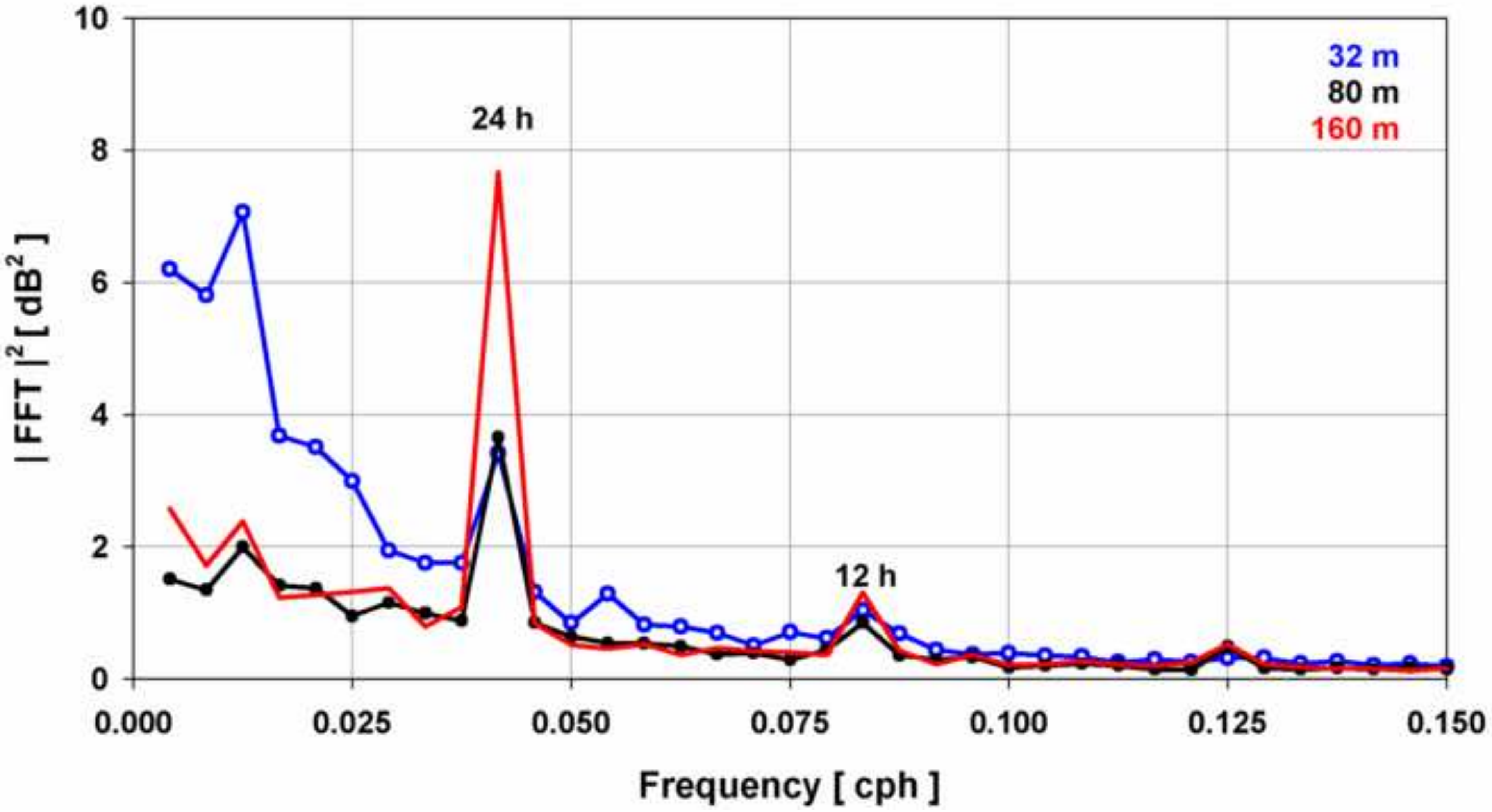

Figure_6

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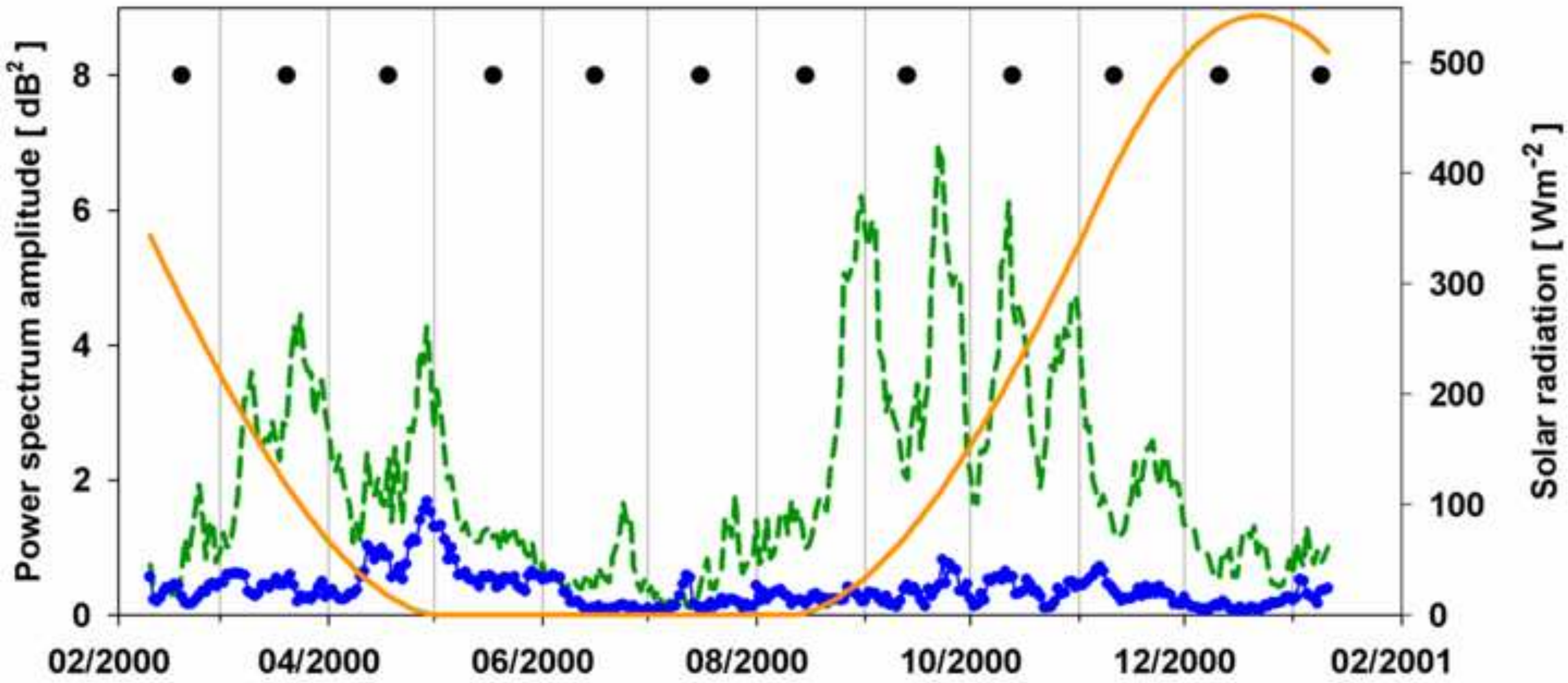


Figure_7

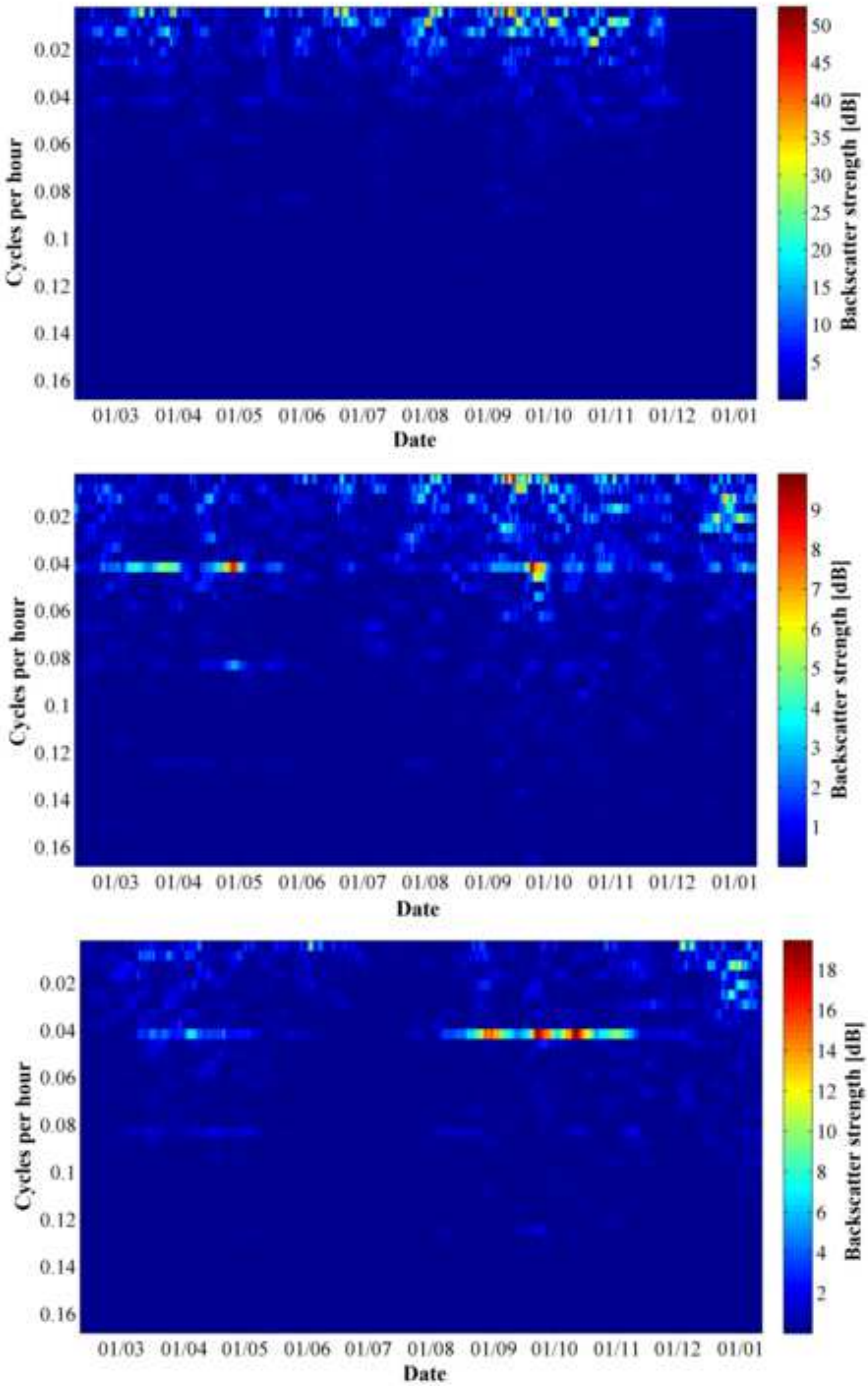

Cycles per hour
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
01/03
01/04
01/05
01/06
01/07
01/08
01/09
01/10
01/11
01/12
01/01
Date
Backscatter strength [dB]
50
45
40
35
30
25
20
15
10
5
Cycles per hour
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
01/03
01/04
01/05
01/06
01/07
01/08
01/09
01/10
01/11
01/12
01/01
Date
Backscatter strength [dB]
9
8
7
6
5
4
3
2
1
Cycles per hour
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
01/03
01/04
01/05
01/06
01/07
01/08
01/09
01/10
01/11
01/12
01/01
Date
Backscatter strength [dB]
18
16
14
12
10
8
6
4
2

Figure_8

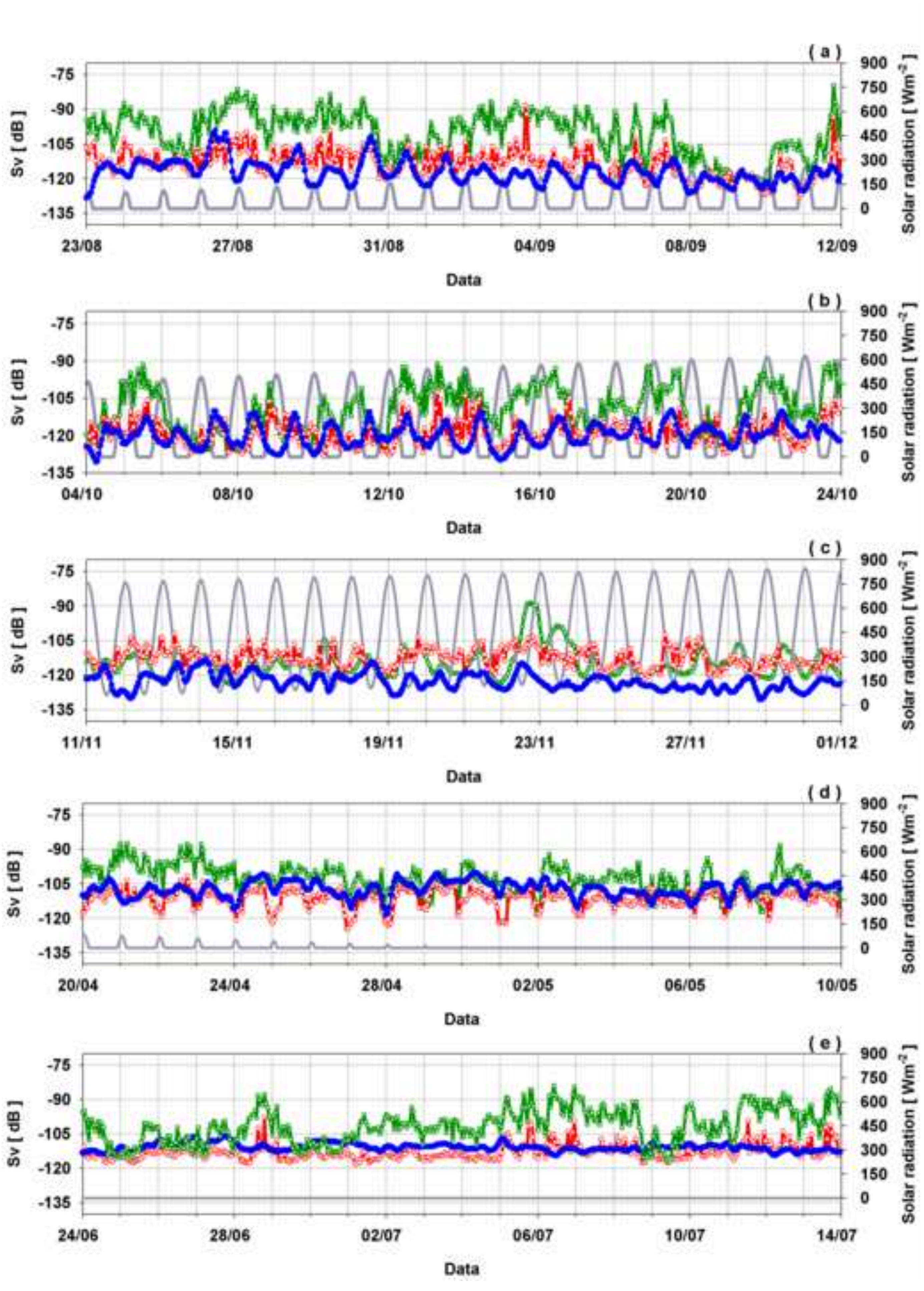
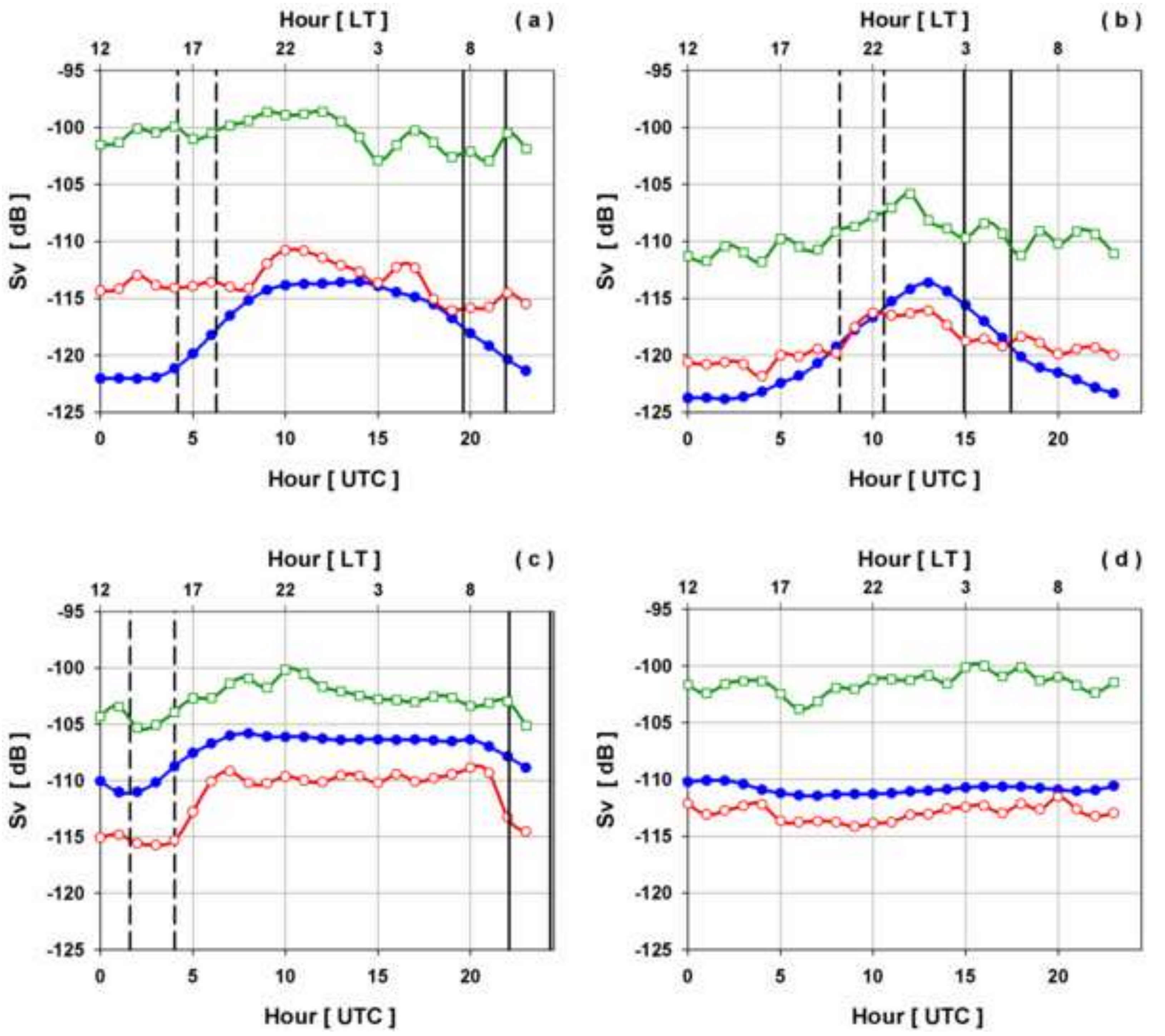

(a)
(b)
(c)
(d)
(e)
Sv [dB]
-75
-90
-105
-120
-135
Solar radiation [Wm^{-2}]
900
750
600
450
300
150
0
Data
23/08
27/08
31/08
04/09
08/09
12/09
04/10
08/10
12/10
16/10
20/10
24/10
11/11
15/11
19/11
23/11
27/11
01/12
20/04
24/04
28/04
02/05
06/05
10/05
24/06
28/06
02/07
06/07
10/07
14/07

Figure_9


Hour [LT]
(a)
(b)
(c)
(d)
12
17
22
3
8
-95
-100
-105
-110
-115
-120
-125
Sv [dB]
0
5
10
15
20
Hour [UTC]

Highlights