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Time-frequency analysis of migrating zooplankton in the Terra Nova Bay polynya (Ross Sea, Antarctica)

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ABSTRACT

An upward-looking 150 kHz narrow-band Acoustic Doppler Current profiler was operated in Terra Nova Bay (Ross Sea, Antarctica) from 5 February 2000 to 16 January 2001 to monitor marine currents. The instrument sampled the upper 160 m of the water column with a time resolution of 1 h. Although the experimental setup was not specifically designed to assess zooplankton and fish distributions and behaviour, the Acoustic Doppler Current Profiler ancillary data provided useful information regarding the diel vertical migration of these acoustic targets. A time frequency analysis of the mean backscatter strength time series was conducted using a 240 h-wide window with a 1 day step. Assuming that the 24 h 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 was analysed. The migration signal was very weak during summer, December to January, but was evident at the beginning and end of the polar night. Interestingly, the results indicated four "migratory blooms," the first at the end of August and the others approximately every three weeks subsequently, ending at the end of October. The daily migration was found to have a good relation with the solar cycle, while it was apparently uncorrelated with the moon phase. Migration patterns in the upper and the lower ocean layers displayed significant differences. Due to the lack of contemporary in-situ net samples, the results are more qualitative than quantitative; nonetheless, they demonstrate the validity of the method to extract relevant information even when applied to data obtained from a non-devoted low-resolution system. This may be of particular interest in polar areas where it is difficult to perform continuous biological monitoring but where a long time series of Acoustic Doppler Current profiler data is available.

1. Introduction

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

Polynyas are special areas for polar marine life because they are almost entirely free from ice and, at the end of the polar night, solar radiation immediately penetrates the water, producing early warming and irradiance that can stimulate relatively early seasonal phytoplankton production (Tremblay et al., 2007). This high primary productivity sustains a food-rich area for higher trophic levels (Hopkins, 1987; Karnowsky et al., 2007), attracting animals as large as marine mammals, which also take advantage of these ice-free areas for breathing.

Zooplankton can be regarded as the trophic link between primary producers and higher trophic levels. Despite their importance, studies on this fundamental component of the Antarctic ecosystem are still limited, largely due to the lack of a long time series with continuous data. In fact, for most of the year, the sea-ice coverage does not allow for in-situ sampling. In the Ross Sea and in Terra Nova Bay, several experimental

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studies have been 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 for these regions (Pinkerton et al., 2010; Tagliabue and Arrigo, 2003); however, few long-term observations are available for the whole year. Thus, much important information about the zooplankton abundance during the entire annual cycle is gathered through indirect observations, such as data obtained from the analysis of faecal pellets collected in sediment traps (Accornero et al., 2003).

Acoustic measurements are widely used to remotely observe oceans, and dedicated instrumentation on a wide range of frequencies is now available for the detection of zooplankton and fishes of different sizes (Brierley et al., 2006; Briseño-Avena et al., 2015; Lemon et al., 2012). An additional source of acoustic data stems from the by-products of Acoustic Doppler Current Profilers (ADCPs). Despite being designed to perform for 3D current measurements, ADCPs also provide ancillary data, specifically the echo intensity profile, that is dependent on the presence of scatterers (e.g., biomass, sediment, bubbles) in the water column. This type of data has been successfully applied in different scientific investigations (Gostiaux and van Haren, 2010) for the detection of zooplankton migration (Flagg and Smith, 1989; van Haren, 2007), suspended sediments (Jourdin et al., 2014; Russo and Boss, 2012), and sea surface conditions (Hyatt et al., 2008; van Haren, 2001). The use of ADCP data could be a great advantage for long-term investigations in polar areas, where direct sampling and 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 made in Terra Nova Bay to investigate the dynamics in the upper layers of the ocean (Cappelletti et al., 2010). To investigate the zooplankton dynamics of the region, particularly with regard to their migration patterns, occurrence and seasonal cycle, the echo intensity data collected by ADCP were examined. The methods used here allow ADCP ancillary time series data to be analysed more objectively and quantitatively than other methods that are primarily based on visual and qualitative assessments.

The lack of concurrent biological samples did not allow for 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 only suitable for identifying the vertical migratory patterns of zooplankton. Despite this, the results can still give provide indications of the behaviour of some specific taxa in the area during the experiment. Additionally, this analytical method can be applied to the historical time series of ADCP data collected in the area for other purposes, furthering the knowledge of Antarctic zooplankton behaviour, especially during winter periods when net samples cannot be taken.

2. Materials and methods

2.1. Experimental setup

An oceanographic mooring (D2) equipped with an upward-facing 150 kHz narrow-band ADCP was kept in operation in Terra Nova Bay (74°55.11′ S; 164°20.4′ E) from 5 February 2000 to 16 January 2001 (Fig. 1). The mooring was deployed at a depth of 600 m, and an ADCP was mounted at a depth of 178 m and set to sample the water column up to the surface at a vertical resolution of 16 m. The middle of the deepest level was 160 m. The ping frequency was set at 1 min. To reduce the standard deviation of each measurement, the instrument was programmed to provide the average of the output data obtained over a one hour period.

Two Aanderaa RCM7 Eulerian current meters were also mounted on the same mooring, at 89 m and 179 m. A second mooring (D1), equipped with Eulerian current meters and temperature and salinity sensors, was located in the same area (75°07.61′ S; 164°27.10′ E, depth of 1100 m) and provided a one year time series of temperature and salinity from fixed sensors at 126 m and 526 m. During the mooring deployment and recovery, CTD casts were performed to provide summer temperature and salinity profiles for the area. The environmental conditions during the study period were obtained from the available oceanographic, meteorological and satellite observations.

The meteorological parameters, including wind speed, wind direction, atmospheric pressure and air temperature, were collected by the Antarctic Weather Station ENEIDE (74°42′ S; 164°6′ E), the closest land-based meteorological station to the study area. Direct solar radiation measurements were available only for early November to mid-February, so the theoretical no-sky solar radiation was computed using the MatLab® air-sea toolbox version 2.0:8/9/99. This parameter is the clear-sky solar radiation computed without any attenuation due to atmosphere. It was used to infer the seasonal and daily cycle of irradiance and ranges between 0 and 884 W/m^2 at the latitude of this mooring. Sea ice concentration data at a 25-km resolution between 164° E to 165.5° E and 74.5° S to 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 study

Sea-ice coverage satellite data allowed for the generation of a rough estimate of the temporal evolution of the Terra Nova Bay polynya extension and, consequently, allowed for a determination of when the sea surface on the mooring location was ice-free. The temporal data of the sea-ice concentration were extracted from the pixel closest to the position of the mooring and indicated that the ice never completely covered the area during the study period. The most sea ice coverage occurred during June to October, but was <20% in February. The strong katabatic westerly winds associated with an increase in air temperature supported a large polynya area, while the sea ice concentration expanded after periods of low wind, such as the second half of May and mid-March.

The sea currents were mainly barotropic, moving northeast at a mean speed of approximately 30 cm/s (Cappelletti et al., 2010). From February to April, they had a slower speed and moved eastward. In the upper 16 m, the horizontal currents were strongly wind-driven and reached hourly mean velocities of almost 70 cm/s. In the surface layer, the vertical velocities were very strong, with peaks up to 20 cm/s, and highly variability, particularly in December, when, notwithstanding the low wind intensity, the vertical motions were intensified by thermohaline forcing due to early ice melting. At deeper depths along the entire water column, the greatest vertical velocities occurred between June and October. These corresponded with increased salinity associated with episodes of dense water formation, while slower vertical velocities characterized the summer season from December to February.

The temperature and salinity time series available at 126 m showed evidence of mixing with fresh water derived from ice melt. The salinity reached a minimum (34.54 psu) 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 a result of the ice melt, summer CTD casts showed a surface layer with a salinity of <34 psu and slightly warmer waters (just above zero degrees) that enhanced the generally weak vertical stratification. During winter, uniform temperatures hovered around the freezing point, while strong mixing and dense water formation made the water column vertically unstable. It should be noted that at this latitude, the polar night lasted from April 29 to August 11 and the midnight sun period was from November 3 to February 8.

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