ARTICLE IN PRESS
MARSYS-02867; No of Pages 12
Journal of Marine Systems xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Journal of Marine Systems
journal homepage: www.elsevier.com/locate/jmarsys

Mesoscale and high-frequency variability of macroscopic particles (>100 μm) in the Ross Sea and its relevance for late-season particulate carbon export

Alexander B. Bochdansky [a,*], Melissa A. Clouse [a], Dennis A. Hansell [b]

[a] Ocean, Earth and Atmospheric Sciences, Old Dominion University, Norfolk, VA, USA
[b] Department of Ocean Sciences, University of Miami, Miami, FL, USA

ARTICLE INFO

Article history:
Received 8 January 2016
Received in revised form 13 August 2016
Accepted 18 August 2016
Available online xxxx

Keywords:
Marine snow
Particulate flux
Patchiness
Spatial variations
Vertical distribution
Video particle profiler
Digital holographic microscope
Heterogeneity
Mesoscale variability
Phytoplankton
Zooplankton
Ross Sea
Antarctica

ABSTRACT

The Ross Sea plays a major role in the transfer of organic carbon from the surface into the deep sea due to the combination of high seasonal productivity and Antarctic bottom water formation. Here we present a particle inventory of the Ross Sea based on a combined deployment of a video particle profiler (VPP) and a high-resolution digital holographic microscope (DIHM). Long-distance (100 s of kilometers) and short-distance (10 s of kilometers) sections showed high variability of particle distributions that co-varied with the density structure of the water column. Particle export was apparent at sites of locally weakened pycnoclines, likely an indirect effect of nutrient mixing into the surface layer and local blooms that lead to export. Particle volume abundances at 200–300 m depth were highly correlated with particle volume abundances in the upper mixed layer (<60 m), consistent with particles at depth primarily the result of export rather than lateral advection. *Phaeocystis antarctica* (Haptophyta) colonies that were initially retained in the mixed layer sank below the euphotic zone within a period of two weeks. Fine-scale analysis at a resolution < 1 m revealed a significantly overdispersed (i.e., highly patchy) environment in all casts. Patchiness, as determined by the Lloyd index of patchiness and the Index of Aggregation, increased in and below the pycnocline presumably due to aggregation of particles while accumulating on density gradients. In contrast, particles in the upper mixed layer and in the nepheloid layers were more randomly distributed. In 40 of the 84 VPP depth profiles, a periodicity of particle peaks ranged from 10 to 90 m with a mode of 30 m, which can be regarded as the “relevant scale” or “characteristic patch size” of the vertical distribution of particles. While chlorophyll fluorescence and particle mass determined by VPP were significantly correlated at higher particle abundances, the relationship changed from cast to cast, reflecting changes in the relative contribution of fresh phytoplankton to total particle mass. Particles that sank below the main pycnocline were composed of phytoplankton, marine snow with and without embedded phytoplankton, crustacean plankton, and a surprisingly high percentage of heterotrophic (and perhaps mixotrophic) protists, such as acantharians and tintinnids.

1. Introduction

The nutrient-rich Ross Sea is the site of massive seasonal blooms of phytoplankton (primarily diatoms and *Phaeocystis antarctica*) and the accumulation of dissolved and particulate organic carbon (Carlson et al., 2000; DiTullio et al., 2010). Particle export in the Ross Sea has commonly been measured with sediment traps (e.g., Asper and Smith, 1999; Smith and Dunbar, 1998; Accornero et al., 1999), and the POC inventory of the water column has been measured on several expeditions using Niskin bottles and GF/F filters that capture particulate matter > ~0.7 μm (e.g., Carlson et al., 2000). However, particles between 50 μm to several millimeters contribute most to the mass flux, as smaller particles do not sink sufficiently fast and larger particles are too rare to play a major role as determined by Guidi et al. (2008) and McDonnell and Buesseler (2010). The smallest particles in this size range are primarily composed of single diatom cells ballasted by their silica skeletons (McDonnell and Buesseler, 2010). Surveys of these critical larger particles are rare, especially in the Ross Sea (Asper and Smith, 2003). Optical backscatter and beam transmissometry are responsive to fine particles and colloidal material (Battisto et al., 1999; Bochdansky et al., 2010), while large particles are more efficiently observed with camera systems (Stemmann et al., 2000; Guidi et al., 2008; Iversen et al., 2010). In order to better understand the composition as well as the spatial and

* Corresponding author.
E-mail address: abochdan@odu.edu (A.B. Bochdansky).

http://dx.doi.org/10.1016/j.jmarsys.2016.08.010

Please cite this article as: Bochdansky, A.B., et al., Mesoscale and high-frequency variability of macroscopic particles (>100μm) in the Ross Sea and its relevance for late-season ..., J. Mar. Syst. (2016), http://dx.doi.org/10.1016/j.jmarsys.2016.08.010

temporal distributions of macroscopic particles in the Ross Sea during the late season, we deployed a video particle profiler (VPP) in combination with a digital holographic microscope (DIHM).

2. Methods

2.1. Research expedition details

Data presented in this manuscript were collected on the RVIB *Nathaniel B Palmer* from February 12 to March 16, 2013 (cruise number NBP-1302). The main focus was on the western Ross Sea as it represents a significant site for Antarctic Bottom Water formation (Fig. 1). During this time period, the Ross Sea transitioned from being almost ice free to almost completely ice covered. We focused on three areas in the western Ross Sea: north of Franklin Island, south of Coulman Island, and Terra Nova Bay, each of which we revisited several times during the expedition in order to record temporal changes. Terra Nova Bay was the site of highest drawdown of inorganic carbon of all sites visited during this expedition (DeJong et al., 2015). We performed short-distance transects to obtain insight into the high-resolution spatial variability, and one long-distance zonal transect across the Ross Sea at the 76° 30′S line (Fig. 1), a section visited during many previous research cruises (e.g., Carlson et al., 2000; Smith et al., 2013). Casts used in this analysis (Fig. 1, Supplementary Table A1) are identified as those where either the VPP (dot) or the DIHM (triangle) or both (square) were deployed. The CTD with instruments was lowered at 0.5 m s^{-1} for the first 100 m, and then accelerated to 1 m s^{-1} for the remainder of each cast.

2.2. Video particle profiler (VPP)

The VPP was similar to that published in Bochdansky et al. (2010). However, instead of 45° angle lighting from both sides, side lighting with two white high-intensity LED lights was used ~7 cm in front of the lens. Some backscatter from transparent exopolymers (TEP), or from small particles embedded in that matrix, was possible using high intensity light. The light beams were restricted using a slit width of 1 cm; however, as the light intensity dropped exponentially in the front and back of the image beam, only the brightest lit image plane was used for analysis. This method reduced bias caused by overlapping particles, removed motion blur streaks, and provided more accurate particle size estimates. At the focal plane, the field of view was 3.5 cm tall and 4.7 cm wide. The analysis program for the VPP was expanded from that in Bochdansky et al. (2010) to include more variables for particle characterization (including perimeter, volume and porosity). The VPP can record 30 images per second, with image analysis by a Linux-based image analysis program (an adapted Avidemux video editing software) at high speeds (approximately in real time after retrieval). The images were later aligned with depth from the CTD using time as the common variable and by filming a clock displaying UTC at the beginning and the end of each video sequence. In Matlab, CTD data were matched at one second resolution with the particle data. The raw data consisted of millions of particles with associated CTD data. These raw data allow us to resample particle metrics at all scales. Particle volumes were calculated as shown in Fig. 2. Instead of assuming a specific geometric shape, the projected area of the particle on the screen (sum of white and black pixels within the perimeter of the particle) was converted into a circle that was then converted to volume. This method reduces error in volume calculations greatly because 2-dimensional information rather than 1-dimensional information is used to reconstruct volumes, thus avoiding the bias of assigning disproportionally large volumes to elongated objects. This approach is widely used in image analysis of ocean particles (e.g., Iversen et al., 2010). Total particle volume ($pixel^3$ $frame^{-1}$) was approximated by multiplying the mean volume of particles with the mean particle number.

2.3. Digital inline holographic microscopy (DIHM)

Details of the DIHM were published in Bochdansky et al. (2013). Briefly, a laser beam is focused on a 9 μm single-mode optical fiber that serves as a small but intense point source of light. The expanding beam intercepts particles that create interfering shadow images on the adjacent screen of a high-resolution (4.2 megapixel) charge-coupled device (CCD) camera without lens. The camera was connected

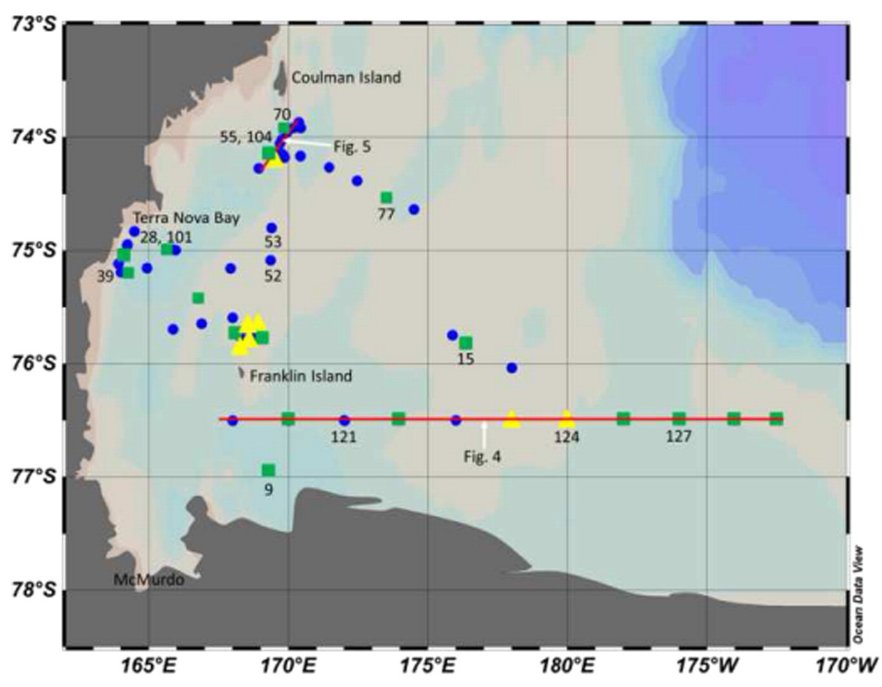

Fig. 1. Locations of casts at which the VPP and the DIHM were deployed during the TRACERS research expedition, February 12 to March 16, 2013. Symbols: VPP only (dots), DIHM only (triangles), and both VPP and DIHM (squares) were successfully deployed. The positions of the short and long transects are indicated by red lines. Casts specifically mentioned in the text and in the figures are labeled. Supplementary Fig. A1 includes cast 15 in the transect that had the highest *Phaeocystis* colony numbers during the entire expedition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Please cite this article as: Bochdansky, A.B., et al., Mesoscale and high-frequency variability of macroscopic particles (>100μm) in the Ross Sea and its relevance for late-season ..., J. Mar. Syst. (2016), http://dx.doi.org/10.1016/j.jmarsys.2016.08.010