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Net community production in the South China Sea Basin estimated from *in situ* O_2 measurements on an Argo profiling float

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ABSTRACT

For the first time, the net community production (NCP) was estimated over a complete annual cycle in the basin of the South China Sea (SCS) using *in situ* oxygen measurements from an Argo profiling float and an oxygen mass balance model. The annual NCP from July 2014 to July 2015 was estimated to be 2.7 mol C m^{-2} yr^{-1} (calculated to the deepest winter mixed layer depth of 56 m), with the uncertainties ranging from 0.9 ~ 2.2 mol C m^{-2} yr^{-1}. NCP estimates followed a monsoonal pattern with higher values in the cold season (November to April) when northeast monsoon prevailed and low values in the warm season (June to September) when this area was dominated by the southwest monsoon. Most of the net heterotrophic events occurred in the warm season. The magnitude and seasonal pattern derived from our results agree with previous export production studies based on discrete measurements. Comparison with satellite-derived NCP revealed that the results derived with NPP from Carbon-based Production Model (CbPM) were closer to the Argo measurements than the results derived with NPP from Vertically Generalized Production Model (VGPM) in magnitude; while the VGPM-based approach did a better job in reproducing the seasonal cycle of NCP in this area. This novel approach provides the possibilities to study the carbon cycle in the SCS with a much higher temporal and spatial resolution, as well as more insights for metabolic state in the oligotrophic subtropical gyres.

1. Introduction

The biological transfer and export of organic carbon from the surface ocean into the deep sea, commonly referred to as the marine biological pump, plays an important role in regulating the atmospheric CO_2 level (Sigman and Boyle, 2000; Ciais et al., 2013). At steady state, the magnitude of net community production (NCP), defined as the gross primary production minus the community respiration, equals to the amount of biologically-produced organic matter available for export and hence can be regarded as one of the best proxies to quantify carbon export efficiency of marine biological pump (Del Giorgio and Duarte, 2002; Ducklow and Doney, 2012).

Whether the metabolic state in the oligotrophic subtropical gyres is autotrophic or heterotrophic is still under extensive debate (Ducklow and Doney, 2012; Duarte et al., 2013; Williams et al., 2013): shipboard based incubation (*in vitro*) approaches (mostly light-dark bottle incubations) tend to yield heterotrophy whereas most results from incubation-free (*in situ*) methods suggest autotrophy in these oligotrophic waters. The major cause for this discrepancy probably lies in the biases associated with one or both types of methodologies (*in vitro* and *in situ*). Also, it can be induced by sampling bias (*e.g.* the two different methods measured NCP at different time and/or locations). The controversy over the sign of NCP cannot be easily solved due to the complicated controlling mechanisms on NCP, which is not only affected by the local primary production, but also related to the dynamics of trophic status and dissolved organic carbon distribution (Arístegui and Harrison, 2002; Serret et al., 2015). If there is some mechanism to deliver semi-labile organic matters from coastal areas to the ocean gyre, the persistent heterotrophic state of the oligotrophic ocean gyre suggested by the *in vitro* measurements could be real (Duarte et al., 2013).

Satellite-based algorithms have been widely utilized to determine the global distribution of NCP and/or particulate export production. Westberry et al. (2012) calculated global NCP using empirical relationships between *in vitro* photosynthesis /respiration and Carbon-

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based Productivity Model (CbPM, Behrenfeld et al., 2005). Using satellite observations of net primary production and particle size distribution, Siegel et al. (2014) developed a food-web model to estimate the global particulate export production. Li and Cassar (2016) presented two statistical algorithms for predicting global NCP based on satellite observations and *in situ* O_2/Ar-NCP measurements. Satellite-based NCP estimates show strong geographic variability with high values in the equator and the subarctic ocean but low NCP in the subtropical gyres. However, this latitudinal trend has been recently challenged by local observations. For example, Emerson (2014) summarized the global observations of annual NCP in the open ocean, ranging from 2 to 4 mol C m^{-2} yr^{-1} without significant latitudinal tendency. This problem remains unsolved due to the limited *in situ* observational estimates available for validation of satellite remote sensing algorithms.

Recently, continuous *in situ* observations of chemical tracers (*e.g.* oxygen, nitrate) using autonomous profiling floats and gliders provide a new approach for NCP measurements (*e.g.* Nicholson et al., 2008; Riser and Johnson, 2008; Bushinsky and Emerson, 2015; Plant et al., 2016; Yang et al., 2017). The best advantage of this approach is that, besides providing long-term, high temporal-resolution measurements of oxygen, it is incubation free, thereby circumventing most of the problems of the shipboard light-dark bottle measurements. It is also suitable for remote areas that are under-sampled.

We take the advantage of the availability of a floating Argo equipped with ship-board calibrated oxygen sensor already deployed in the basin of the South China Sea (SCS), which is the largest subtropical marginal sea in the world. The SCS is strongly affected by seasonal monsoons, which drive the surface circulation to an anti-cyclonic gyre in the summer and to a cyclonic gyre in the winter (Hu et al., 2000). Southwest monsoon is predominant between June and September, while the northeast monsoon starts in October and dominates the winter until early spring. The transition between these two monsoon periods takes places in May and October. Under the influence of the East Asian Monsoon System, distinctive seasonal variations have been observed in different biogeochemical parameters such as nutrients (Wong et al., 2007; Du et al., 2013), net primary production (Ning et al., 2004; Tan and Shi, 2009), new production (Lee Chen, 2005), and dissolved organic carbon (Wu et al., 2015). Studies based on ^{14}C incubation method in the SCS have shown the net primary production changing from 45 mmol C m^{-2} d^{-1} in the winter to a lower value of 32 mmol C m^{-2} d^{-1} in the summer (Ning et al., 2004). A mean primary production value of 29 mmol C m^{-2} d^{-1} in the SCS was estimated based on remote sensing (SeaWiFS) data (Liu et al., 2002). Annual export production in the SCS have also been estimated by various approaches such as ^{234}Th-based particular organic carbon (POC) exports (Cai et al., 2015; Chen et al., 2008), sediment traps (Chen et al., 1998), numerical models (Liu et al., 2002; Liu and Chai, 2009), $^{15}NO_3$ uptake incubation experiments (Lee Chen, 2005), and nutrients budgets (Hung et al., 2007), with a range of 0.8–3.1 mol C m^{-2} yr^{-1}. For direct measurements of NCP in this area, however, there is only one field study conducted in the summer using the light-dark bottle method (Wang et al., 2014). The results therein showed that in the summer the autotrophic state dominated the coastal area whereas the net heterotrophic state dominated the SCS basin. The lack of temporal and spatial coverage for NCP studies remains a critical issue for further evaluation of the biological pump efficiency and carbon cycling in the SCS. Here, we strive to obtain high temporal resolution of NCP estimates in the SCS basin based on the continuous O_2 measurements on an Argo profiling float. Our aim is to provide a more comprehensive and unbiased picture of NCP in the SCS basin and, more broadly, to add more insights into the unresolved debate on the autotrophy *versus* heterotrophy in oligotrophic ocean gyres.

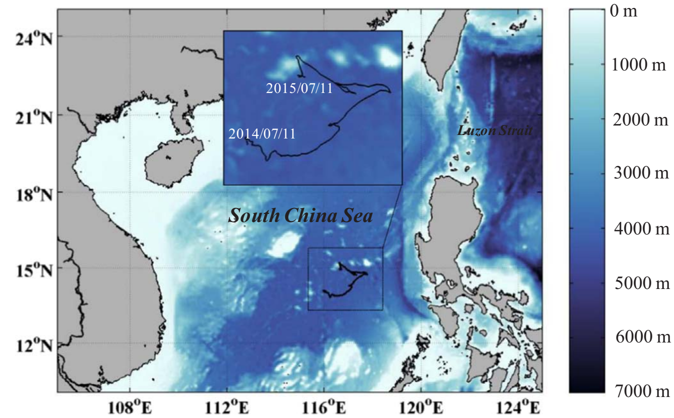

Fig. 1. Study area in the basin of the South China Sea. The black line represents the Argo float trajectory. The sampling period is from July 11th, 2014 to July 11th, 2015.

2. Materials and methods

2.1. Study area

The study area (13.8°N–15.2°N, 115.9–117.8°E) is located in the center of the SCS basin (Fig. 1). This area is characterized as a tropical oligotrophic environment due to the stratification and isolation by circulation gyres (Ning et al., 2004; Wong et al., 2007), with relatively low surface chlorophyll *a* (Chl-*a*) concentrations ranging from 0.02 to 0.24 $\mu g\ L^{-1}$ (Zhang et al., 2016). In the summer when strong stratification occurs, both concentrations of nitrate and phosphorus in the upper layer are usually below the detection limit (0.3 μM for nitrate and 0.01 μM for phosphorus, Wong et al., 2007). In the winter, the sea surface is cooled by the northeast monsoon and the mixed layer deepens (Wong et al., 2007). As a result, more nutrients can be entrained into the euphotic zone in the winter and lead to greater phytoplankton biomass and primary production (Liu et al., 2002; Lee Chen and Chen, 2006). For comparison, the time period from November to April of the following year is defined as the cold season when northeast monsoon prevails, and the time period from June to September is defined as the warm season when southwest monsoon prevails.

2.2. Argo deployment and oxygen sensor calibration

The Argo profiling float (Sea-Bird Navis BGCi, No. F0348) used in this study was equipped with a SBE 41CP CTD, a SBE 63 optical dissolved oxygen sensor, and a WET Labs ECO-MCOMS fluorometer (Zhang et al., 2016). The profiling cycle was set to be 1–5 days. The vertical resolution was approximately 2 m from surface to 1000 m depth and 50 m below 1000 m depth. 143 profiles were obtained from July 11th, 2014 to July 11th, 2015. The raw O_2 data were calibrated against discrete samples collected from the CTD cast at the time of float deployment (0 − 150 m, measured using spectrophotometric Winkler method, Pai et al., 1993). A linear regression yielded the following calibration equation: $[O_2]_{Winkler} = 1.0912\ (\pm 0.017) \times [O_2]_{Sensor} - 11.658\ (\pm 3.025)$ ($R^2 = 0.977$, $n = 6$, Fig. S1). The details of calibration are presented in the Supplementary material.

2.3. Upper ocean oxygen mass balance model

The float data (temperature, salinity, $[O_2]$) were binned into 2-week average and then interpolated into a model grid with 1-m depth resolution and one-day time interval. We adopted a simplified two-layer O_2 mass balance model (Yang et al., 2017) to estimate the NCP in the upper ocean (Fig. 2). Layer 1 represents the mixed layer, which was determined using the temperature-based criteria (the depth with 0.2 °C temperature difference from 10 m, De Boyer Montégut et al., 2004).