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Spatial distribution and controlling factors of planktonic foraminifera in the modern western Pacific

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ABSTRACT

Studies of the spatial distribution of living planktonic foraminifera in modern water columns are still lacking in the western Pacific. In this study, 40 plankton tows at 8 stations were conducted, focusing on the terminus of the North Equatorial Current (NEC) and its two bifurcated branches in the western Pacific. The results show that planktonic foraminifera were in high abundance around the Kuroshio Current (KC) source region and the Mindanao Current (MC) system but in low abundance in the NEC. The planktonic foraminiferal assemblage was dominated by *G. sacculifer* and *G. ruber*, with relative abundances of 44.0% and 27.3%, respectively. According to a cluster analysis of the results of seven stations, the stations can be divided into three groups, namely, Group NEC, Group KC and Group MC, which displayed different features of planktonic foraminiferal assemblages. The low abundance of planktonic foraminifera that characterized the NEC stations may be induced by the thick mixed layer and deep thermocline/nutricline in this region. However, stations in the KC region, which also had thick mixed layers and deep thermoclines, showed higher abundances of planktonic foraminifera than the NEC stations. This result was probably caused by the higher terrigenous input. The planktonic foraminifera show the highest abundance at the MC stations, which may be the result of existing upwelling conditions.

1. Introduction

Planktonic foraminifera are major biogenetic calcium carbonate producers in the surface waters of open oceans (Schiebel, 2002). The faunal assemblages and the element/isotope composition of their fossil shells are popularly used in paleoceanography based on the assumption that the surrounding environmental conditions control the distributions and shell compositions of different planktonic foraminifera (Manno and Pavlov, 2014; Kuroyanagi and Kawahata, 2004). Regional variations exist in the distribution of extant planktonic foraminifera. In the modern ocean, there are some species abundant in tropical and subtropical waters, such as *G. sacculifer*, *G. ruber* and *P. obliquiloculata* (Kucera and Darling, 2002; Pflaumann and Jian, 1999). However, some species are apt to survive in middle to high latitude waters, such as *Neogloboquadrina pachyderma* (Darling et al., 2004). In addition, some shallow dwelling opportunistic species are abundant in high productivity areas and are often used as upwelling intensity indicators, such as *G. bulloides* (Kucera, 2007). The distribution and abundance of planktonic foraminifera can be used for reconstructing paleotemperature, paleosalinity and paleoproductivity (Chen et al., 1999; Xiang et al., 2009). For example, a number of statistical methods for SST (Sea Surface Temperature) reconstruction, such as the modern analog technique (MAT), were established using the relationship between planktonic foraminiferal assemblages of core-top sediments and SSTs in the local area (Katz et al., 2010; Mix et al., 1999). Food availability in the upper water column can also be reflected by planktonic foraminiferal assemblages, although different feeding

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strategies exist (Fairbanks et al., 1980, 1982; Ortiz et al., 1995).

In recent years, the oxygen and carbon isotopic compositions and Mg/Ca ratio of foraminiferal shells have become common tools for paleoceanographic studies and are combined to reconstruct paleotemperature, global ice volume, and ocean surface productivity (Katz et al., 2010). In addition to these traditional proxies, geochemical proxies are emerging based on the planktonic foraminiferal shells, such as planktonic foraminiferal calcite Ba/Ca (Hall and Chan, 2004), B/Ca and U/Ca (Yu and Elderfield, 2007; Russell et al., 2004), and the size normalized weight of planktonic foraminiferal tests (Bijma et al., 1999; Barker and Elderfield, 2002). These proxies could be used to reconstruct variations of fluvial inputs to the ocean (Weldeab et al., 2007), carbonate ion concentration [CO_3^{2-}] and seawater pH (Foster, 2008; Michael et al., 2015; Moy et al., 2009; Weinkauf et al., 2016).

The proxies mentioned above are very useful for reconstructing the past climate and environment of oceans worldwide in the last several decades. However, the paleoceanography research in the western Pacific is relatively weaker compared with other regions, such as the South China Sea (Tian et al., 2002; Xu et al., 2005) and eastern equatorial Pacific (McClymont et al., 2013; Ford et al., 2015; Foster, 2008). There may be two reasons for this. One reason is that, most parts of the western Pacific have deep water, which will exert a negative effect on the preservation of foraminiferal fossils (Wu and Berger, 1989; Sun et al., 2017; Jian et al., 1999). Consequently, it is very difficult to widely use foraminifera preserved in surface sediments to establish reliable transfer functions or estimation formulas in the entire western Pacific because only the surface sediment samples recovered at depths of less than 3000 m could reasonably be used (Pflaumann and Jian, 1999). Thus, most paleoceanographic studies of the western Pacific have aimed to reconstruct the climate and ocean environmental conditions of the past based mainly on stable isotope compositions and the Mg/Ca ratios of their calcite shells preserved in deep ocean sediments (Bolliet et al., 2011; Qiu et al., 2014) and have rarely used other proxies until today. Another important reason is the lack of understanding of the planktonic foraminiferal ecology in this region. The quality of paleoceanographic reconstructions is constrained by the ecological knowledge of the local modern planktonic foraminifera. However, few studies have focused on the relationships between living planktonic foraminifera and environmental conditions in the western Pacific. It is not persuasive enough to apply new proxies in such regions without a thorough investigation of the distribution patterns of planktonic foraminifera and the regional environmental factors that control these patterns. Therefore, it is essential to acquire rich knowledge of the seasonal and depth habitats of planktonic foraminifera for paleoceanography reconstruction in the western Pacific.

Three approaches are commonly used to study modern planktonic foraminifera, such as laboratory cultures, sediment traps and plankton tows. Laboratory culture experiments in controlled environments can quantitatively provide detailed information on the relationships between planktonic foraminifera and environmental conditions (Spero et al., 1997). Nevertheless, the field environment is more complex than the laboratory environment, and elemental or isotope signals of foraminiferal shells are influenced by multiple environmental drivers. For example, the shell weight of planktonic foraminifera was reported as correlative to the carbonate ion concentration in culture experiments (Bijma et al., 1999; Russell et al., 2004). However, when this relationship was assessed in sediment core-top samples, the shell weight of planktonic foraminifera was also controlled by temperature and nutrient levels (Villiers, 2004). Therefore, the laboratory cultures need to be combined with field research. Sediment traps and plankton tows are commonly used approaches for field research of modern planktonic foraminifera. The sediment trap method gives time series information that documents the seasonal and annual variability in the assemblage composition and flux of planktonic foraminifera living in the upper water column of a localized area (Lin and Hsieh, 2007; Lin et al., 2011; Sagawa et al., 2013). In recent years, sediment traps have been commonly used from the tropical Solomon Sea to the subpolar Japan Sea, involving the North Equatorial Current (NEC), the Kuroshio Current (KC), the South China Sea and other adjacent currents or water masses.

Most modern planktonic foraminiferal studies are based on sediment traps in the western Pacific in the past few years. In the Western Pacific Warm Pool, a high planktonic foraminiferal flux has been reported during winter monsoon periods, which is attributed to the wind-driven mixing of surface waters and nutrient advection from coastal waters (Kawahata et al., 2000; Kempe and Knaack, 1996). During a La Niña period, increased precipitation was considered to have increased the planktonic foraminifera flux in the warm pool region (Yamasaki et al., 2008). At the northern edge of the Western Pacific Warm Pool, where the NEC bifurcates into two branches, the planktonic foraminiferal flux decreased following the decrease in precipitation during an El Niño period (Kim et al., 2014). These previous studies have given us foundational knowledge of the temporal variations of planktonic foraminiferal particle fluxes and their relationship with surrounding environmental changes, such as the East Asia Monsoon and ENSO (El Niño Southern Oscillation).

Although sediment trap studies supplied precious information of seasonal and annual variations in foraminiferal assemblages, there is also a need to understand regional variations of foraminiferal faunal distribution and its relationship with environmental parameters. Plankton tows, another field research approach, are used to reveal the spatial distribution of planktonic foraminifera and their relationships with the surrounding environmental conditions and to determine the foraminiferal profile distribution in the water column (Kuroyanagi and Kawahata, 2004). During the last four decades, studies involving the use of plankton tows have significantly increased our knowledge of planktonic foraminiferal ecology for some species (Bé and Hutson, 1977; Fairbanks et al., 1980; Watkins et al., 1996, 1998). These studies revealed the main environmental controls, such as thermal preferences, and food sources for a variety of individual species. Plankton tows have mainly been conducted in the West Pacific marginal seas, such as the South China Sea, and the seas around the Ryukyu Islands and Japan (Lin and Hsieh, 2007; Lin et al., 2011; Kuroyanagi and Kawahata, 2004). However, little is known about the vertical and spatial distribution of planktonic foraminifera in the western Pacific, especially in the Kuroshio source region, the terminus of the NEC at the northern edge of the Western Pacific Warm Pool. In this study, we aimed to investigate the vertical distribution and assemblage of planktonic foraminifera in the western Pacific and to examine the relationship between the living foraminiferal spatial distribution and environmental conditions in the surface water column.

2. Regional setting

The western Pacific is generally considered an oligotrophic area with low-nutrient surface waters (Matsumoto et al., 2004). The Western Pacific Warm Pool, which is the greatest extension of warm surface water in the global open oceans and extends from the western Pacific to the eastern India Ocean, plays an important role in global climate change and ocean evolution (Li et al., 2010). A series of shallow haloclines in this well-stratified water make it difficult to transport nutrients from subsurface water to the surface euphotic layer (Mackey et al., 1995). Four major currents are located