Radiolarian assemblages in the shelf area of the East China Sea and Yellow Sea and their ecological indication of the Kuroshio Current derivative branches (#44305)

Hanxue Qu [Equal first author, 1, 2, 3, 4], **Yong Xu** [Equal first author, 1, 2, 3, 4], **Jinbao Wang** [1, 3, 4], **Xinzheng Li** [Corresp. 1, 2, 3, 4]

[1] Institute of Oceanology, Chinese Academy of Sciences, Qingdao, China
[2] University of Chinese Academy of Sciences, Beijing, China
[3] Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China
[4] Laboratory for Marine Biology and Biotechnology, Qingdao, China

Corresponding Author: Xinzheng Li
Email address: lixzh@qdio.ac.cn

We analyzed the radiolarian assemblages of 59 surface sediment samples collected from the Yellow Sea and East China Sea of the northwestern Pacific. In the study region, the Kuroshio Current and its derivative branches exerted a crucial impact on radiolarian composition and distribution. The results of cluster analysis indicated that the radiolarian assemblages in the East China Sea shelf could be divided into three regional groups, including the East China Sea north region group, the East China Sea middle region group, and the East China Sea south region group. The results of the redundancy analysis suggested that the Sea Surface Temperature, Sea Surface Salinity and silt percentage were primary environmental variables explaining species-environment relationship. The remarkable significance of temperature and salinity, which were important characters of the Kuroshio Current, demonstrate the powerful influence of the Kuroshio Current in the study area.

Deleted: ¶
<object>First submission¶
¶
¶
Guidance from your Editor¶
¶
Please submit by **14 Jan 2020** for the benefit of the authors (and your $200 publishing discount) .¶
¶
<object>Structure and Criteria¶
Please read the 'Structure and Criteria' page for general guidance.¶
<object>
<object>
Raw data check
Review the raw data.
Image check¶
Check that figures and images have not been inappropriately manipulated.¶
¶
Privacy reminder: If uploading an annotated PDF, remove identifiable information to remain anonymous.¶
¶
¶
¶
¶
Section Break (Continuous)
Files¶
¶
<object>Download and review all files from the materials page.¶
Column Break
<object>7 Table file(s)¶
Section Break (Next Page)
¶
¶
Structure and¶
<object>Criteria¶
Column Break
<object>2 ¶
Section Break (Continuous)
¶
¶
¶
Structure your review¶
The review form is divided into 5 sections. Please consider these when composing your review:¶
1. **BASIC REPORTING¶**
2. **EXPERIMENTAL DESIGN¶**
3. **VALIDITY OF THE FINDINGS¶**
4. General comments¶
...

Deleted:

Deleted: showed a

Deleted: by

Radiolarian assemblages in the shelf area of the East China Sea and Yellow Sea and their ecological indication of the Kuroshio Current derivative branches

Hanxue Qu[1, 2, 3, 4], Yong Xu[1, 2, 3, 4], Jinbao Wang[1, 3, 4], Xinzheng Li[1, 2, 3, 4]

[1] Institute of Oceanology, Chinese Academy of Sciences, 7 Nanhai Road, Qingdao 266071, China
[2] University of Chinese Academy of Sciences, Beijing 100049, China
[3] Center for Ocean Mega-Science, Chinese Academy of Sciences, 7 Nanhai Road, Qingdao, 266071, China
[4] Laboratory for Marine Biology and Biotechnology, Pilot National Laboratory for Marine Science and Technology (Qingdao), 1 Wenhai Road, Qingdao 266237, China

Corresponding Author:
Xinzheng Li
7 Nanhai Road, Qingdao, 266071, China
Email address: lixzh@qdio.ac.cn

Abstract

We analyzed the radiolarian assemblages of 59 surface sediment samples collected from the Yellow Sea and East China Sea of the northwestern Pacific. In the study region, the Kuroshio Current and its derivative branches exerted a crucial impact on radiolarian composition and distribution. The results of cluster analysis indicated that the radiolarian assemblages in the East China Sea shelf could be divided into three regional groups, including the East China Sea north region group, the East China Sea middle region group, and the East China Sea south region group. The results of the redundancy analysis suggested that the Sea Surface Temperature, Sea Surface Salinity and silt percentage were primary environmental variables explaining species-environment relationship. The remarkable significance of temperature and salinity, which were important characters of the Kuroshio Current, demonstrate the powerful influence of the Kuroshio Current in the study area.

Key words: Radiolarian assemblages, the Kuroshio Current, shelf area, environmental variables, the East China Sea, the Yellow Sea

Introduction

Polycystine Radiolaria (hereafter Radiolaria), with a high diversity of 300-800 recent species, are a crucial group of marine planktonic protists (Boltovskoy, 2017). Living Radiolaria are widely distributed throughout the shallow-to-open oceans (Wang, 2012), and a proportion of their siliceous skeltons settle on the seafloor after death (Yasudomi et al., 2014). The distribution of Radiolaria in a given region is associated with the pattern of water mass, such as temperature, salinity and nutrients (Anderson, 1983; Hernández - Almeida et al., 2017).

The East China Sea (ECS) and Yellow Sea (YS) are marginal seas of the northwestern Pacific (Xu et al., 2011). The two regions are divided by the line connecting the northern tip of the mouth of the Changjiang and the southern tip of the Jeju Island (Jun, 2014). Hydrographic conditions of the shelf area of both the ECS and YS, where the depth is generally within 100 meters, vary remarkably with the season (Qi, 2014). Generally, the annual sea surface temperature (SST) and sea surface salinity (SSS) show a decreasing trend from the southeast to northwest in study area (Fig. 1).

The Kuroshio Current originates from the Philippine Sea, flows through the ECS, and afterwards forms the Kuroshio Extension (Hsueh, 2000; Qiu, 2001). The Kuroshio Current and its derivative branches, including the Taiwan Warm Current (TWC) and Yellow Sea Warm Current, form the main circulation systems in the shelf area of the YS and ECS (Hsueh, 2000; Qi, 2014). In the ECS shelf region's summer (Fig. 2A), the Kuroshio subsurface water (KSSW) gradually upwells northwestward from east of Taiwan, and finally reaches 30.5°N off the Changjiang

Deleted: showed a
Deleted: by
Deleted: radiolaria
Deleted: is
Deleted: radiolaria
Deleted: is
Deleted: mostly
Deleted: s
Deleted: due to the siliceous skeleton
Deleted: radiolaria
Comment [JR1]: Should be marked on Fig. 1 maps
Comment [JR2]: Less than 100 metres?
Deleted: s
Deleted: summer of
Deleted: at

estuary along ~60 m isobaths, forming the Nearshore Kuroshio Branch Current (Yang et al., 2012; Yang et al., 2011). Meanwhile, the TWC is is formed by the mixing of the Taiwan Strait Warm Current (TSWC) and Kuroshio Surface Water (KSW) (Qi, 2014). In winter (Fig. 2B), the KSW shows relatively intense intrusion as part of the KSW northwestward reaches continental shelf area across 100 m isobaths (Zhao & Liu, 2015). At this point, the TWC is mainly fed from the Kuroshio Current northeast of Taiwan (Qi, 2014).

In summer of the YS shelf region (Fig. 2A), the Yellow Sea Cold Water Mass, characterized by low temperature, occupies the central low-lying area mostly below the 50 m isobaths while the Yellow Sea Warm Current shows little influence (Guan, 1963). In winter (Fig. 2B), the impact of the Yellow Sea Warm Current on shelf region is enhanced, while the Yellow Sea Cold Water Mass disappears (Weng et al., 1989).

The radiolarian assemblages in surface sediments have been investigated in the ECS whereas there are few reports in the YS. These reports cover the ECS including the Okinawa Trough (Chang et al., 2003; Cheng & Ju, 1998; Wang & Chen, 1996) and continental shelf region extensively (Chen & Wang, 1982; Tan & Chen, 1999; Tan & Su, 1982). They summarize the distribution patterns of the dominant species and the environmental conditions that affect the composition of radiolarian fauna in the ECS. However, these investigations, when discussing the relationships between radiolarians and environmental variables, are not based on rigorous statistical analysis. In addition, to which the ECS and YS are influenced by the Kuroshio Current and its derivative branch remains unclear. To solve these questions, the radiolarian data collected from 59 surface sediment samples are associated with environmental variables of the upper water to explore the principal variables explaining radiolarian species composition. The influences of the Kuroshio Current on radiolarian assemblages in the study area are also considerably discussed.

Materials & Methods

Sample collection and treatment

The surface sediments were collected at 59 sites (Fig. 3A) in the Yellow Sea and East China Sea using a box corer. The sediment samples in the study area were divided into four groups geographically and were labeled the Yellow Sea region (YSR) samples, the ECS north region (ECSNR) samples, the ECS middle region (ECSMR) samples, and the ECS south region (ECSSR) samples. The samples were prepared using the method described by Chen et al. (2008). 30% hydrogen peroxide and 10% hydrochloric acid were added to each dry sample to remove organic component and the calcium tests, respectively. Then the treated sample was sieved with a 50 μm sieve and dried in an oven. After flotation in carbon

Deleted: mixed by

Deleted: chiefly originated

Deleted: featured

Deleted: approximately

Deleted: enhances

Deleted: disappeared

Deleted: an extensively large range of

Deleted: ,

Deleted: These reports

Deleted: impact

Deleted: what extent are

Comment [JR3]: Subheadings like this need to be emphasized in some ways (bold, italics ,etc)

Deleted: by

Deleted: According to the geographical position of the

Deleted: , the samples

Deleted: parts

Deleted: , which

Deleted: dealt as

Deleted: process

tetrachloride, the cleaned residue was sealed with Canadian gum for radiolarian identification and quantification under a light microscope with a magnification of 200X or 400X.

Environmental data

Grain size analysis of the surface sediments was conducted with a Laser Diffraction Particle Size Analyzer (Cilas 1190, CILAS, Orleans, Loiret, France). The data were used to categorise grain size classes as clay (1-4 μm), silt (4-63 μm) and sand (63-500 μm), and to determine different sediment types according to the Folk classification (Folk ,Andrews & Lewis, 1970). In addition, the mean grain size was calculated for each site.

The values of annual temperature (SST), salinity (SSS), oxygen, phosphate, nitrate, and silicate of sea surface for the period of 1930 to 2009 were derived from the CARS2009 dataset (Ridgway ,Dunn & Wilkin, 2002). The sea surface chlorophyll-a and particulate organic carbon for the period of 1997 to 2010 were obtained from https://oceancolor.gsfc.nasa.gov/l3/. The values of the environmental variables mentioned above for each surface sediment site were estimated by linear interpolation. Finally, 12 variables were adapted in the statistical analysis, i.e. SST, SSS, oxygen, phosphate, nitrate, silicate, chlorophyll-a, particulate organic carbon, clay percentage, silt percentage, sand percentage, and mean grain size. The values of environmental parameters of each site were shown in Supplementary material Table 1.

Statistical processing

The minimum number of specimens counted in each sample is customarily 300. However, low radiolarian concentrations are frequent in the shelf type sediments comprised mainly of terrigenous sources (Chen et al., 2008). Given small sediment samples, it was difficult to find 300 individuals in some sites. Therefore, the threshold number of radiolarians was adjusted to 100, which is sufficient for a reliable interpretation of species proportions (Fatela & Taborda, 2002). Based on this threshold, 24 samples (Fig. 3B) were retained for detailed statistical analysis. We calculated the absolute abundance (inds.$(100g)^{-1}$) and the diversity index, including the number of species (S), Margalef's index (d), Shannon-Wiener's index (H' ($\log_e$)), Simpson index ($1 - \lambda'$) and Pielou's evenness (J'). Relative abundance (%) of each radiolarian taxon was also calculated. Then the hierarchical cluster analysis with group-average linking was applied to analyze the variations of radiolarian assemblage among different regions. The raw data of the relative abundance was transformed by square root. Afterwards, triangular resemblance matrix was constructed based on the Bray-Curtis similarity (Clarke & Warwick, 2001). Analysis of similarity (ANOSIM) was employed to determine the differences among different assemblages. Similarity percentage procedure (SIMPER) analysis was used to identify the species that contributed most to the similarities among radiolarian assemblages.

Comment [JR4]: Carbon tetrachloride is a liquid & is not used in solution.
Deleted: solution
Deleted: textural
Deleted: identify
Deleted: , including
Deleted: Moreover
Deleted: Also, the
Formatted: Indent: Left: 0.44 cm
Deleted: derived
Deleted: All¶ 100 environmental data
Deleted: were interpolated to
Deleted: using linear¶ 101 method
Comment [JR5]: Not obvious what this is intended to mean.
Deleted: counting
Deleted: s
Deleted: should be 300 in general
Deleted: frequently occurs
Deleted: that
Deleted: limited
Deleted: is
Deleted: count
Deleted: is
Comment [JR6]: This statement needs expansion to justify the decision.
Comment [JR7]: "individuals" presumably – "tests" would be better.
Comment [JR8]: Insufficient information – I cannot reproduce this.
Comment [JR9]: Percentages so no longer raw!
Comment [JR10]: Why?

Detrended correspondence analysis (DCA) was applied to determine the character of the species data. The gradient length of the first DCA axis was 1.768 < 3, suggesting that redundancy analysis (RDA) was more suitable (Lepš & Šmilauer, 2003). RDA was used to evaluate the relationship between environmental variables and radiolarian assemblages identified by SIMPER analysis. The species abundance data was square root transformed before analysis to reduce the effect of extremely high values (Ter Braak & Smilauer, 2002). Variance inflation factors (VIF) was calculated to screen the environmental variables with VIF > 10. Sand percentage, mean grain size, chlorophyll-a, silicate, oxygen, and particulate organic carbon were removed from the RDA model step by step, in order to avoid collinearity (Naimi et al., 2014). Finally, six variables, SST, SSS, silt percentage, clay percentage, nitrate, and phosphate, were employed in the RDA. The significant environmental variables were determined by automatic forward selection with Monte Carlo tests (999 permutations). Station DH 8-5 was excluded from the RDA analysis for for lack of environmental data.

Correlation analysis was employed to investigate the relationship between the dominant radiolarian taxa and significant environmental variables.

The diversity indices calculation, cluster analysis, ANOSIM, and SIMPER were performed by PRIMER 6.0. Correlation analysis was performed by SPSS 20. DCA and RDA were conducted by CANOCO 4.5.

Results

The radiolarian abundance in the ECS and YS shelf area

According to the Folk classification, the sediments of the shelf area in the ECS and YS consisted mainly of silty sand, sandy silt and silt (Fig. 4). The non-zero absolute abundance of radiolarians in each site showed no significant correlation with grain size parameter, including sand percentage (n = 42, p = 0.668), clay percentage (n = 42, p = 0.465), silt percentage (n = 42, p = 0.761), as well as mean grain size (n = 42, p = 0.637).

A total of 142 radiolarian taxa (Supplementary material Table 2) were identified from the surface sediments of study area, including 75 genera, 14 families and 3 orders. The raw radiolarian counting data is shown in Supplementary material Table 3. Approximately 91.0% of the species belonged to Spumellaria, accounting for the vast majority of the radiolarian fauna. Nassellaria and Collodaria accounted for 8.4% and 0.6%, respectively. Pyloniidae definitely dominated in the species composition as it occupied approximately 61%, followed by Spongodiscidae 17%, and Coccodiscidae 8% (Fig. 5A).

Radiolarian abundance in surface sediments varied greatly in study area (Fig. 5B). An abundance ranking of ECSMR > ECSSR > ECSNR > YSR was detected in study area. In addition,

Comment [JR11]: I cannot reproduce this value.

Comment [JR12]: More suitable than what? CCA?

Deleted: collinerity

Deleted: 6

Deleted: including

Deleted: lacking

Comment [JR13]: This should be deleted & the information included as colums B & C in Table 3 to make the rest of this paragraph easier to follow.

Deleted: was

radiolarians exhibited a quite low abundance value in the YSR, as no individuals were found in 15 sites of the YS.

Selected stations with radiolarian individuals ≥ 100

According to Table 1, there exists a significant difference in radiolarian abundance between the different regions ($p < 0.05$). Besides, species diversity indices (including S, d, H'(log_e), J', 1-λ') showed significant differences (one-way ANOVA or Kruskal-Wallis Test, $p < 0.05$) among three regions and displayed an overall ranking of ECSSR > ECSMR > ECSNR.

Cluster analysis based on the relative abundance classified all but one site into three regional groups, including the ECSNR group, ECSMR group and ECSSR group (Fig. 6). The significant differences among the three groups were examined by ANOSIM (Global R = 0.766, p = 0.001). The dominant species in each regional group were identified by SIMPER analysis with a cut-off of 50% (Table 2). Tetrapyle octacantha, Didymocyrtis tetrathalamus, and Spongodiscus resurgens dominated in the ECSNR group, with contribution of 41.16%, 10.46%, and 9.13%, respectively. The radiolarian taxa, including T. octacantha, Didymocyrtis tetrathalamus, Stylodictya multispina, Zygocircus piscicaudatus, and Spongaster tetras, contributed most to the ECSMR group. The dominant species in the ECSSR group were composed of T. octacantha, Didymocyrtis tetrathalamus, Spongaster tetras, Dictyocoryne profunda, Z. piscicaudatus, Stylodictya multispina, Phorticium pylonium, and Spongodiscus resurgens.

It was indicated by the RDA that the first two axes explained 37.2% (RDA1 27.6%, RDA2 9.6%) of the species variance, and 70.5% of the species-environment relation variance (Table 3A). Forward selection with Monte Carlo test (999 Permutation) revealed that sea surface temperature (SST), sea surface salinity (SSS), and silt percentage were the most significant environmental variables associated with radiolarian composition (Table 3B).

The RDA plot showed a clear distribution pattern of regional samples (Fig. 7A). The ECSNR samples generally occupied the left part of the ordination, showing a feature of comparatively lower SST, while additionally a wide range of SSS and silt percentage. The ECSMR samples were mostly located in the middle part, suggesting an adaption to a higher value of SST, SSS, and lower silt percentage. The ECSSR samples distributed mainly at right part, characterized by the higher value of SST and SSS. Moreover, the ECSSR samples showed an extensive fitness to SSS.

The dominant species identified by the SIMPER analysis (Table 2) were displayed in the RDA plot (Fig. 7B). Species taxa, including Spongaster tetras, Dictyocoryne profunda and P. pylonium, were related to higher SST and silt percentage, while showed little relationship with

Deleted: existed

Deleted: among

Comment [JR14]: The description of Table 1 - not useful here.

Deleted: Different lowercase a, b and c indicate significant differences among regional groups.¶
165 Abbreviations: N, Abundance (inds.(100g)$^{-1}$); S, number of species; d, Margalef's index; J',¶
166 Pielou's index; H' (log_e) , Shannon-Wiener's index; 1-λ', Simpson index.

Deleted: axis

Comment [JR15]: I could not repeat this.

SSS. Zygocircus piscicaudatus, and Stylodictya multispina displayed a preference of higher silt percentage, SST, and lower SSS. Didymocyrtis tetrathalamus was positively related to SST and SSS, while scarcely influenced by silt percentage. Tetrapyle octacantha showed a better fitness to higher SSS, lower SST, and lower silt percentage. Additionally, Spongodiscus resurgens was negatively associated with SST and SSS, while little associated with silt percentage.

Discussion

Low radiolarian abundance in the ECS and YS shelf area

Generally, the number of the radiolarian individuals in continental shelf sediments of the ECS and YS is several orders of magnitude lower than that of the adjacent Okinawa trough (Chang et al., 2003; Cheng & Ju, 1998). First, due to the continental runoff input, coastal area water is featured of lower temperature and salinity, resulting in lower number of living radiolarians (Chen & Wang, 1982; Tan & Su, 1982). Also, deposition rate in study area is considerably high as 0.1–0.8 cm/yr in the YS, and 0.1–3 cm/yr in the ECS (Dong, 2011), which greatly masks the concentration of radiolarian skeleton in sediments (Chang et al., 2003).

In particular, only a small number of radiolarians were detected in the YS, as no radiolarians were detected in the 15 sites within the range of the central YS (Fig. 5B). The low abundance of radiolarian individuals is probably controlled by the Yellow Sea Cold Water Mass that exists in the central YS (Guan, 1963; Liu et al., 2018). The low temperature and salinity (Fig. 1) of the cold water mass make it quite difficult for radiolarians to survive and proliferate.

Selected stations with radiolarian individuals ≥ 100

In the ECS, the gradients of SST and SSS are controlled by the interaction of the Kuroshio branch current, TWC and Changjiang Diluted Water (Yang et al., 2012). SST and SSS both show an increase from north to south, corresponding well with the overall distribution of radiolarians (Fig. 1, Fig. 5).

Revealed by the RDA, SST was the most significant environmental variable related to the radiolarian composition, followed by SSS, and silt percentage (Table 3B). SST is generally regarded as having an extremely important role in controlling the composition and distribution of of radiolarians (Boltovskoy & Correa, 2017; Hernández‐Almeida et al., 2017; Ikenoue et al., 2015). For a long time, the relationship between radiolarian assemblages and SST is used to construct past changes in hydrographic conditions (Matsuzaki & Itaki, 2017). In this study, SST showed a significant correlation with abundance, species number, d, and H’ (Table 4), suggesting that higher SST may often correspond to higher diversity.

SSS was also crucial for explaining species-environment correlations in the ECS shelf area. At the offshore Western Australia, salinity is strongly significant in determining radiolarian species

Deleted: amount
Deleted: existed
Deleted: er
Deleted: that
Deleted: denoting
Deleted: always
Deleted: s

distributions (Rogers, 2016). Hernández - Almeida et al. (2017) and Liu et al. (2017a) stated that the composition and distribution pattern of the radiolarian fauna in the western Pacific responds mainly to SST and SSS. Gupta (2002) found that the relative abundance of Pyloniidae exhibits a positive correlation with salinity. In this study SSS was positively correlated to abundance, species number and d (Table 4), similarly suggesting a positive influence of SSS on radiolarian diversity.

Silt percentage significantly affected the radiolarian species composition in study area. Previous researchers indicated that the preservation of radiolarian tests is influenced by sediment type, as radiolarian skeleton generally achieves good preservation in fine sediment (Chen & Wang, 1982; Wang & Chen, 1996). The radiolarian abundance and species number decreases with increased grain size (Chang et al., 2003). Here silt percentage showed no significant correlation with N and S at the 5% level, while it showed significant correlation with J' and H' (Table 4), suggesting positive relationship between radiolarian diversity and silt percentage.

The radiolarian assemblages of the ECSSR group were influenced by the Kuroshio Current and TWC, while the TWC predominated. The surface water of the TWC is mainly characterised by high temperature (23-29°C) and sub-high salinity (33.3-34.2psu) (Weng & Wang, 1988). Some of the TWC waters are supplemented from the South China Sea (Liu et al., 2017b), where radiolarians show high diversity (Chen et al., 2008; Liu et al., 2017a; Zhang et al., 2009).

The dominant species in the ECSSR group included T. octacantha, Didymocyrtis tetrathalamus, Spongaster tetras, Dictyocoryne profunda, Z. piscicaudatus, Stylodictya multispina, Phorticium pylonium, and Spongodiscus resurgens (Table 2, Fig. 8). These species taxa, except Spongodiscus resurgens, are reported as typical indicators of the Kuroshio Current (Chang et al., 2003; Gallagher et al., 2015; Liu et al., 2017a; Matsuzaki ,Itaki & Kimoto, 2016). The relatively high abundance of these taxa in the study area reflected the influence of the warm Kuroshio and TWC waters. Moreover, moderate percentage of Pterocorys campanula (0.91%) was detected in the ECSSR group, in contrast with the ECSMR group (0.14%) and ECSNR group (0.06%). Pterocorys campanula is a warm-water species that frequently occurs and dominates in the South China Sea, whereas there are no reports of the dominance of P. campanula in the ECS (Chen & Tan, 1996; Chen et al., 2008; Hu et al., 2015; Liu et al., 2017a). The high abundance of this taxa in the ECSSR group further demonstrates our conclusion that radiolarian assemblages of the ECSSR group were brought by the Kuroshio Current and TWC with the TWC playing the main role.

The ECSMR group was influenced by the Kuroshio Current, TWC, and Changjiang Diluted Water. The dominant species in the ECSMR included T. octacantha, Didymocyrtis tetrathalamus, Stylodictya multispina, Z. piscicaudatus, and Spongaster tetras (Table 2). The

Deleted: in the western Pacific

Deleted: indicating

Comment [JR16]: No. It possibly affected the preservation of tests.

Deleted: distribution

Deleted: well

Comment [JR17]: No. Preservation, not diversity.

Deleted: featured

Comment [JR18]: Meaning?

Comment [JR19]: Mixed fonts

Deleted: with high abundance

Deleted: for

Deleted: er

Deleted: , while

Deleted: plays a

dominant species of the ECSMR group showed great overlap with the ECSSR group, which, in some degrees, suggests a similarity between the two groups, as both are influenced by the the Kuroshio Current and TWC. On the other hand, the lower percentages of these taxa indicated part of the impact by the Changjiang Diluted Water, which is characterized by lower SST and SSS (Fig. 8).

Tetrapyle octacantha, Didymocyrtis tetrathalamus, and Spongodiscus resurgens were dominant species of the ECSNR group, which was primarily impacted by the Changjiang Diluted Water and Kuroshio Current. Compared to the ECSMR and ECSSR group, the ECSNR group occupied higher latitude which means a lower SST, while the large input of Changjiang Diluted Water decreased SSS (Fig. 1). This combination of lower SST and SSS probably hindered the radiolarian diversity of the ECSNR (Table 1).

The radiolarian assemblages in the shallower sea, i.e., the shelf sea area of the ECS, displayed distinctly different patterns from those in the open ocean. Tetrapyle octacantha occurred in the extraordinarily high proportion of 59% in the study area (Fig. 8), much higher than ever reported in adjacent areas with deeper waters (Chang et al., 2003; Cheng & Ju, 1998; Liu et al., 2017a; Wang & Chen, 1996). Tetrapyle octacantha, as the most abundant taxon in the subtropical area (Boltovskoy, 1989), shows a high tolerance to temperature (Ishitani et al., 2008). This taxon has been reported to be associated with water from the ECS shelf area (Chang et al., 2003; Itaki ,Kimoto & Hasegawa, 2010). Zhang et al. (2009) found that T. octacantha frequency was negatively correlated with SST, and Welling & Pisias (1998) concluded that T. octacantha dominated during the cold tongue period. In our study, T. octacantha was negatively related to SST according to the results of the RDA (Fig. 7B), tending to confirm the previous studies. We thus infer that T. octacantha is possibly more resistant to local severe conditions and, so, reaches comparatively high abundance in the shelf area. Therefore, T. octacantha can serve as an indicator that depicts the degree of mixture between the colder shelf water and warm Kuroshio water.. Spongodiscus resurgens, with an upper sub-surface maximum, was generally considered to be cold water species (Suzuki & Not, 2015) and related to productive nutrient-rich water (Itaki ,Minoshima & Kawahata, 2009; Matsuzaki & Itaki, 2017). The ECSNR group was primarily controlled by the colder Changjiang Diluted Water, and thus had the highest percentage of T. octacantha and Spongodiscus resurgens among three regions

Deleted: suggested the
Deleted: were
Deleted: hence
Deleted: additionally
Deleted: of ECSNR
Deleted: Unlike the radiolarian assemblages in the open ocean, the
Deleted: showed
Deleted: averagely
Deleted: which was
Deleted: conditions
Deleted: Also,
Deleted: to
Deleted: conforming to

Conclusions

We analyzed radiolarian assemblages collected from the YS and ECS shelf area, where the Kuroshio Current and its derivative branches, including the TWC and Yellow Sea Warm Current, exerts great effect.

(1) The radiolarian abundance in the YS was quite low, due to the influence of the Yellow Sea Cold Water Mass.

Comment [JR20]: How do we know?

(2) The radiolarian abundance and diversity in the ECS , which is controlled by the Kuroshio warm water, was much higher. Based on the cluster analysis, the radiolarian assemblages in the ECS could be divided into three regional groups, namely the ECSNR group, ECSMR group and ECSSR group.

Formatted: Space Before: 4.1 pt

Deleted: , which was controlled¶ 299 by the Kuroshio warm water

a. The ECSNR group was chiefly impacted by the Changjiang Diluted Water and Kuroshio Current, with dominant species of T. octacantha, Didymocyrtis tetrathalamus, and Spongodiscus resurgens.

b. The ECSMR group was controlled by the Kuroshio Current, TWC and Changjiang Diluted Water. Species contributed most to this group included T. octacantha, Didymocyrtis tetrathalamus, Stylodictya multispina, Z. piscicaudatus, and Spongaster tetras.

c. The ECSSR group was affected by the Kuroshio Current and TWC, in which the TWC occupies major status. The dominant species in this group were composed of T. octacantha, Didymocyrtis tetrathalamus, Spongaster tetras, Dictyocoryne profunda, Z. piscicaudatus, Stylodictya multispina, P. pylonium, and Spongodiscus resurgens.

(3) The RDA results showed that SST, SSS and silt percentage were main environmental variables ($p < 0.05$) that influenced the radiolarian composition in the ECS shelf. SST and SSS are closely related to the character of the Kuroshio Current water, while silt percentage is associated with the preservation of radiolarian skeleton in sediments.

Supplementary material

Supplementary material Table 1, Environmental parameters of the 59 surface sediment samples.

Supplementary material Table 2, Taxonomic status of the total radiolarian taxa identified in study area.

Supplementary material Table 3, Raw counting data of the total radiolarian assemblages in the 59 surface sediment samples.

Acknowledgements

We thank laboratory members for collecting samples of this study. We also thank L. L. Zhang of the South China Sea Institute of Oceanology, Chinese Academy of Sciences, for the valuable suggestions on the manuscript.

References

Anderson OR. 1983. Radiolaria. New York: Springer Science & Business Media.

Boltovskoy D. 1989. Radiolarian record of the last 40,000 years in the western equatorial Pacific. Oceanologica Acta 12:79-86.

Boltovskoy D. 2017. Vertical distribution patterns of Radiolaria Polycystina (Protista) in the World Ocean: living ranges, isothermal submersion and settling shells. Journal of Plankton Research 39:330-349. https://doi.org/10.1093/plankt/fbx003

Boltovskoy D, Correa N. 2017. Planktonic equatorial diversity troughs: fact or artifact? Latitudinal diversity gradients in Radiolaria. Ecology 98:112-124. https://doi.org/10.1002/ecy.1623

Chang FM, Zhuang LH, Li TG, Yan J, Cao QY, Cang SX. 2003. Radiolarian fauna in surface sediments of the northeastern East China Sea. Marine Micropaleontology 48:169-204. https://doi.org/10.1016/s0377-8398(03)00016-1

Chen MH, Tan ZY. 1996. Radiolaria from surface sediments of the central and northern South China Sea. Beijing: Science Press.

Chen MH, Zhang LL, Zhang L, Xiang R, Lu J. 2008. Preservation of radiolarian diversity and abundance in surface sediments of the South China Sea and its environmental implication. Journal of China University of Geosciences 19:217-229. https://doi.org/10.1016/s1002-0705(08)60041-2

Chen W, Wang B. 1982. A preliminary study on the Radiolaria from surface sediments of the East China Sea (in Chinese). Marine Geological Research 2:59-r69.

Cheng Z, Ju X. 1998. Radiolaria From the Surface Sediments in the Middle Okinawa Trough (in Chinese). Oceanologia et Limnologia Sinica 29:662-665.

Clarke K, Warwick R. 2001. Changes in Marine Communities: An Approach to Statistical Analysis and Interpretation. 2nd ed. Plymouth: PRIMER-E Ltd.

Dong A. 2011. Source, Sink and its Environmental Record of Sediments in Yellow Sea and East China Sea. Ocean University of China.

Fatela F, Taborda R. 2002. Confidence limits of species proportions in microfossil assemblages. Marine Micropaleontology 45:169-174. https://doi.org/10.1016/s0377-8398(02)00021-x

Folk RL, Andrews P, Lewis DW. 1970. Detrital sedimentary rock classification and nomenclature for use in New Zealand. New Zealand Journal of Geology & Geophysics 13:937-968. http://dx.doi.org/10.1080/00288306.1970.10418211

Gallagher SJ, Kitamura A, Iryu Y, Itaki T, Koizumi I, Hoiles PW. 2015. The Pliocene to recent history of the Kuroshio and Tsushima Currents: a multi-proxy approach. Progress in Earth and Planetary Science 2. https://doi.org/10.1186/s40645-015-0045-6

Guan B. 1963. A preliminary study of the temperature variations and the characteristics of the circulation of the cold water mass of the Yellow Sea (in Chinese). Oceanologia et Limnologia Sinica 5:255-284.

Gupta SM. 2002. Pyloniid stratigraphy–a new tool to date tropical radiolarian ooze from the central tropical Indian Ocean. Marine Geology 184:85-93. https://doi.org/10.1016/S0025-3227(01)00276-6

Hernández-Almeida I, Cortese G, Yu PS, Chen MT, Kucera M. 2017. Environmental determinants of radiolarian assemblages in the western Pacific since the last deglaciation. Paleoceanography 32:830-847. https://doi.org/10.1002/2017PA003159

Hsueh Y. 2000. The Kuroshio in the East China Sea. Journal of Marine Systems 24:131-139. https://doi.org/10.1016/S0924-7963(99)00083-4

Hu W, Zhang L, Chen M, Zeng L, Zhou W, Xiang R, Zhang Q, Liu S. 2015. Distribution of living radiolarians in spring in the South China Sea and its responses to environmental factors. Science China Earth Sciences 58:270-285. https://doi.org/10.1007/s11430-014-4950-0

Ikenoue T, Bjørklund K, Kruglikova S, Onodera J, Kimoto K, Harada N. 2015. Flux variations and vertical distributions of siliceous Rhizaria (Radiolaria and Phaeodaria) in the western Arctic Ocean: indices of environmental changes. Biogeosciences 12. https://doi.org/10.5194/bg-12-2019-2015

Ishitani Y, Takahashi K, Okazaki Y, Tanaka S. 2008. Vertical and geographic distribution of selected radiolarian species in the North Pacific. Micropaleontology:27-39.

Itaki T, Kimoto K, Hasegawa S. 2010. Polycystine radiolarians in the Tsushima Strait in autumn of 2006. Paleontological Research 14:19-32. https://doi.org/10.2517/1342-8144-14.1.019

Itaki T, Minoshima K, Kawahata H. 2009. Radiolarian flux at an IMAGES site at the western margin of the subarctic Pacific and its seasonal relationship to the Oyashio Cold and Tsugaru Warm currents. Marine Geology 255:131-148. https://doi.org/10.1016/j.margeo.2008.07.006

Jun P. 2014. The Delimitation of the Continental Shelf beyond 200 Nautical Miles in the East China Sea. China Oceans L Rev:124.

Lepš J, Šmilauer P. 2003. Multivariate analysis of ecological data using CANOCO. Cambridge: Cambridge university press.

Liu L, Zhang Q, Chen M, Zhang L, Xiang R. 2017a. Radiolarian biogeography in surface sediments of the Northwest Pacific marginal seas. Science China Earth Sciences 60:517-530. https://doi.org/10.1007/s11430-016-5179-4

Liu W, Song J, Yuan H, Li N, Li X, Duan L. 2017b. Dissolved barium as a tracer of Kuroshio incursion in the Kuroshio region east of Taiwan Island and the adjacent East China Sea (in Chinese). Science China Earth Sciences:160-171.

Liu X, Liu Q, Zhang Y, Hua E, Zhang Z. 2018. Effects of Yellow Sea Cold Water Mass on marine nematodes based on biological trait analysis. Marine Environmental Research 141:167-185. 10.1016/j.marenvres.2018.08.013

Matsuzaki KM, Itaki T. 2017. New northwest Pacific radiolarian data as a tool to estimate past sea surface and intermediate water temperatures. Paleoceanography 32:218-245. http://dx.doi.org/10.1002/2017PA003087

Matsuzaki KM, Itaki T, Kimoto K. 2016. Vertical distribution of polycystine radiolarians in the northern East China Sea. Marine Micropaleontology 125:66-84. https://doi.org/10.1016/j.marmicro.2016.03.004

Naimi B, Hamm NA, Groen TA, Skidmore AK, Toxopeus AG. 2014. Where is positional uncertainty a problem for species distribution modelling? Ecography 37:191-203.

Qi J. 2014. The study on the Water Masses, Kuroshio and Water Exchange in the East China Sea (in Chinese). Institute of Oceanology, Chinese Academy of Sciences.

Qiu B. 2001. Kuroshio and Oyashio currents. Ocean Currents: A Derivative of the Encyclopedia of Ocean Sciences:61-72. https://doi.org/10.1006/rwos.2001.0350

Ridgway K, Dunn J, Wilkin J. 2002. Ocean interpolation by four-dimensional weighted least squares—Application to the waters around Australasia. Journal of atmospheric and oceanic technology 19:1357-1375. https://doi.org/10.1175/1520-0426(2002)019<1357:oibfdw>2.0.co;2

Rogers J. 2016. Monsoonal and other climatic influences on radiolarian species abundance over the last 35 ka, as recorded in core FR10/95-GC17, off North West Cape (Western Australia). Revue de Micropaleontologie 59:275-293. https://doi.org/10.1016/j.revmic.2016.05.003

Suzuki N, Not F. 2015. Biology and Ecology of Radiolaria. Japan: Springer Japan.

Tan Z, Chen M. 1999. Offshore Radiolaria from China. Bejing: Science Press.

Deleted: radiolaria

Tan Z, Su X. 1982. Studies on the Radiolaria in sediments of the East China Sea (continental shelf). Studia Marina Sinica 19:129-216.

Ter Braak CJ, Smilauer P. 2002. CANOCO reference manual and CanoDraw for Windows user's guide: software for canonical community ordination (version 4.5). Ithaca: Microcomputer Power.

Wang JB. 2012. Study on the Ecology and Taxonomy of polycystine Radiolaria from three aeras of the South China Sea[D] (in Chinese with English summary). Institute of Oceanology, Chinese Academy of Sciences.

Wang R, Chen R. 1996. preliminary study on the Radiolaria from the surface sediments in southern Okinawa Trough (in Chinese). Journal of Tongji University:670-676.

Deleted: radiolaria

Welling LA, Pisias NG. 1998. Radiolarian fluxes, stocks, and population residence times in surface waters of the central equatorial Pacific. Deep Sea Research Part I: Oceanographic Research Papers 45:639-671.

Weng X, Wang C. 1988. On the Taiwan Warm Current Water. Chinese Journal of Oceanology & Limnology:40-49.

Weng X, Zhang Y, Wang C, Zhang Q. 1989. The variational characteristics of the Huanghai Sea (Yellow Sea) cold water mass (in Chinese). Oceanologia et Limnologia Sinica 19:119-131.

Xu D, Li X, Zhu J, Qi Y. 2011. Evaluation of an ocean data assimilation system for Chinese marginal seas with a focus on the South China Sea. Chinese Journal of Oceanology and Limnology 29:414-426. https://doi.org/10.1007/s00343-011-0044-4

Yang D, Yin B, Liu Z, Bai T, Qi J, Chen H. 2012. Numerical study on the pattern and origins of Kuroshio branches in the bottom water of southern East China Sea in summer. Journal of Geophysical Research: Oceans 117. https://doi.org/10.1029/2011jc007528

Yang D, Yin B, Liu Z, Feng X. 2011. Numerical study of the ocean circulation on the East China Sea shelf and a Kuroshio bottom branch northeast of Taiwan in summer. Journal of Geophysical Research: Oceans 116. https://doi.org/10.1029/2010jc006777

Yasudomi Y, Motoyama I, Oba T, Anma R. 2014. Environmental fluctuations in the northwestern Pacific Ocean during the last interglacial period: evidence from radiolarian assemblages. Marine Micropaleontology 108:1-12. https://doi.org/10.1016/j.marmicro.2014.02.001

Zhang LL, Chen MH, Xiang R, Zhang JL, Liu CJ, Huang LM, Lu J. 2009. Distribution of polycystine radiolarians in the northern South China Sea in September 2005. Marine Micropaleontology 70:20-38. https://doi.org/10.1016/j.marmicro.2008.10.002

Zhao RX, Liu ZL. 2015. The seasonal variability of the Kuroshio surface water intrusion onto the East China Sea continental shelf derived from Argos drifter data (in Chinese). Marine Sciences.

Figure 1

The mean annual sea surface temperature (SST, A) and sea surface salinity (SSS, B) in the shelf area of the ECS and YS.

Comment [JR21]: Maps should show locations of Changjiang and Jeju Island

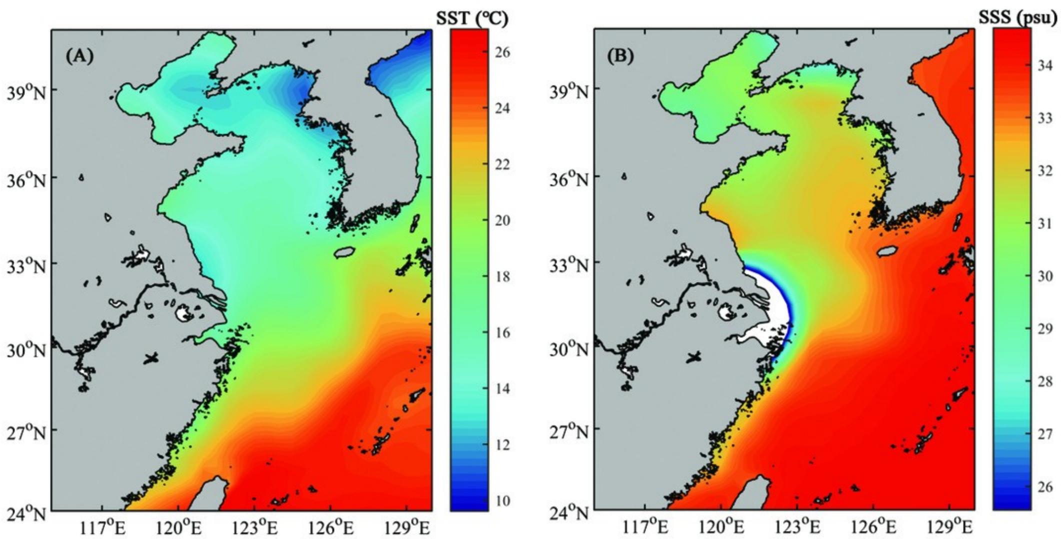
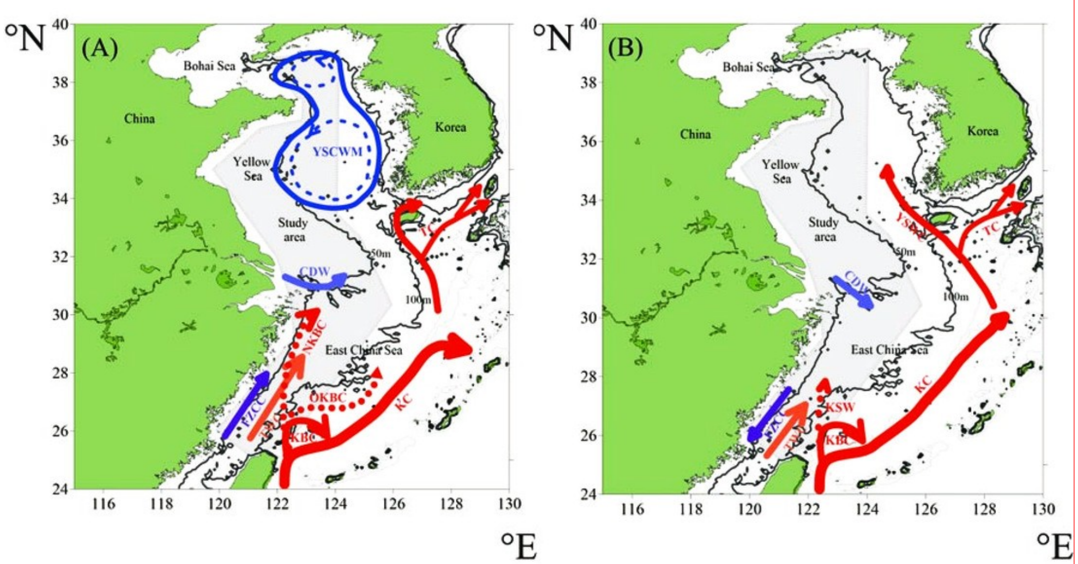


Figure 2

The circulation system of the study area in summer (A) and winter (B) (redrawn after Yang et al. (2012) and Ichikawa & Beardsley (2002)).

Abbreviations: KC – Kuroshio Current, KBC- Kuroshio Branch Current, OKBC - Offshore Kuroshio Branch Current, NKBC - Nearshore Kuroshio Branch Current, KSW - Kuroshio Surface Water, TWC – Taiwan Warm Current, FZCC – Fujian Zhejiang Coastal Current, CDW – Changjiang Diluted Water, YSCWM – Yellow Sea Cold Water Mass, YSWC – Yellow Sea Warm Current, TC - Tsushima Current



Comment [JR22]: Naames of currents hard to read.

Figure 3

The location of the total surface sediment samples in the ECS and YS shelf area (A), and 24 samples for statistical analysis with a threshold of 100 individuals (B).

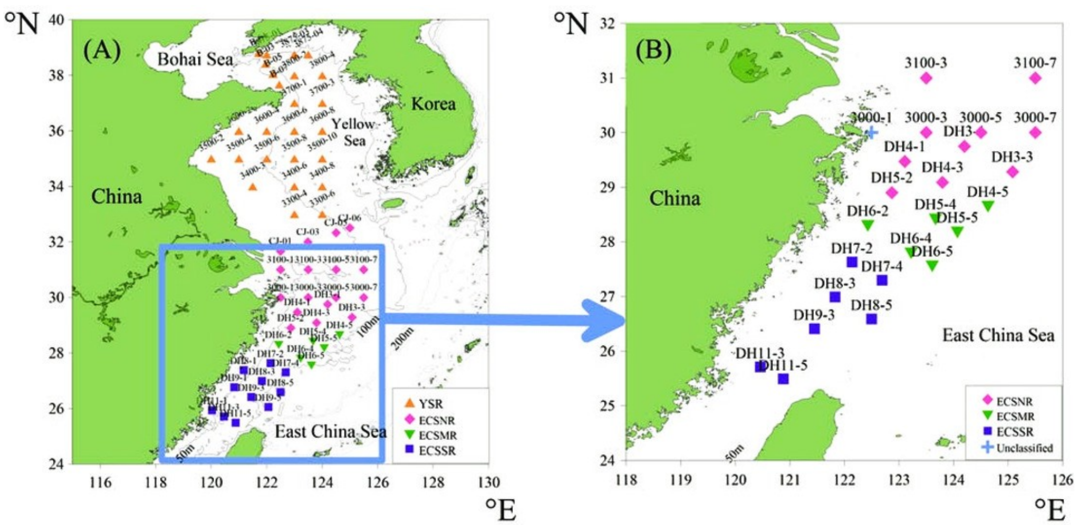


Figure 4

Grain-size distributions of shelf surface sediments in the ECS and YS.

(A) grain size classification, (B) sand percentage, (C) clay percentage, (D) silt percentage.

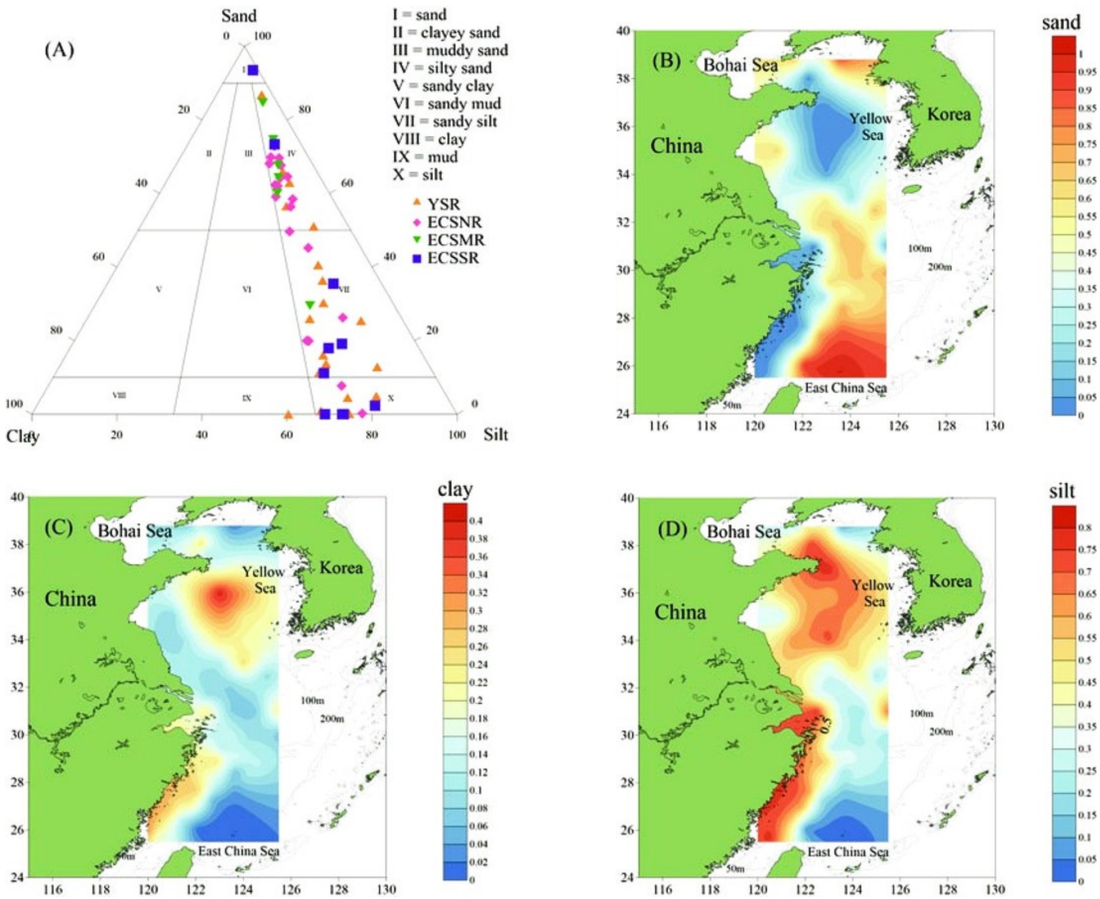


Figure 5

Total relative abundance (%, A), and absolute abundance (inds.$(100g)^{-1}$, B) of the radiolarians in the surface sediments.

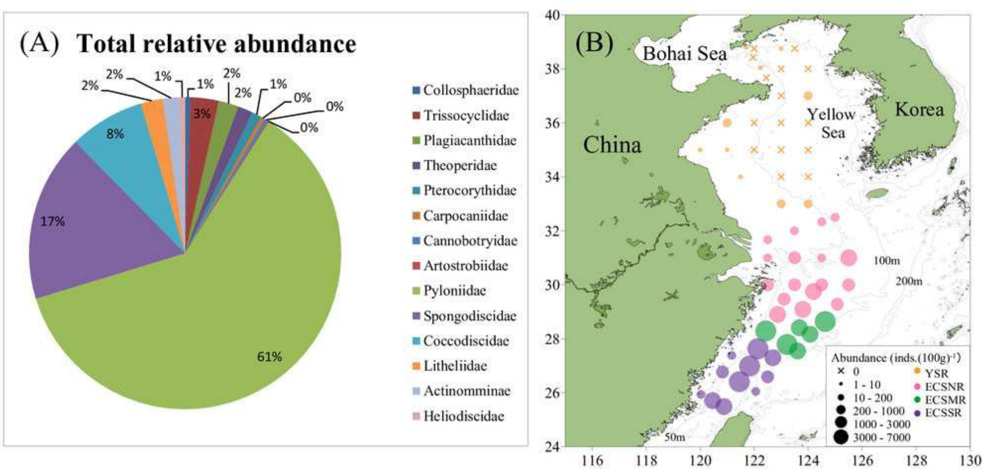
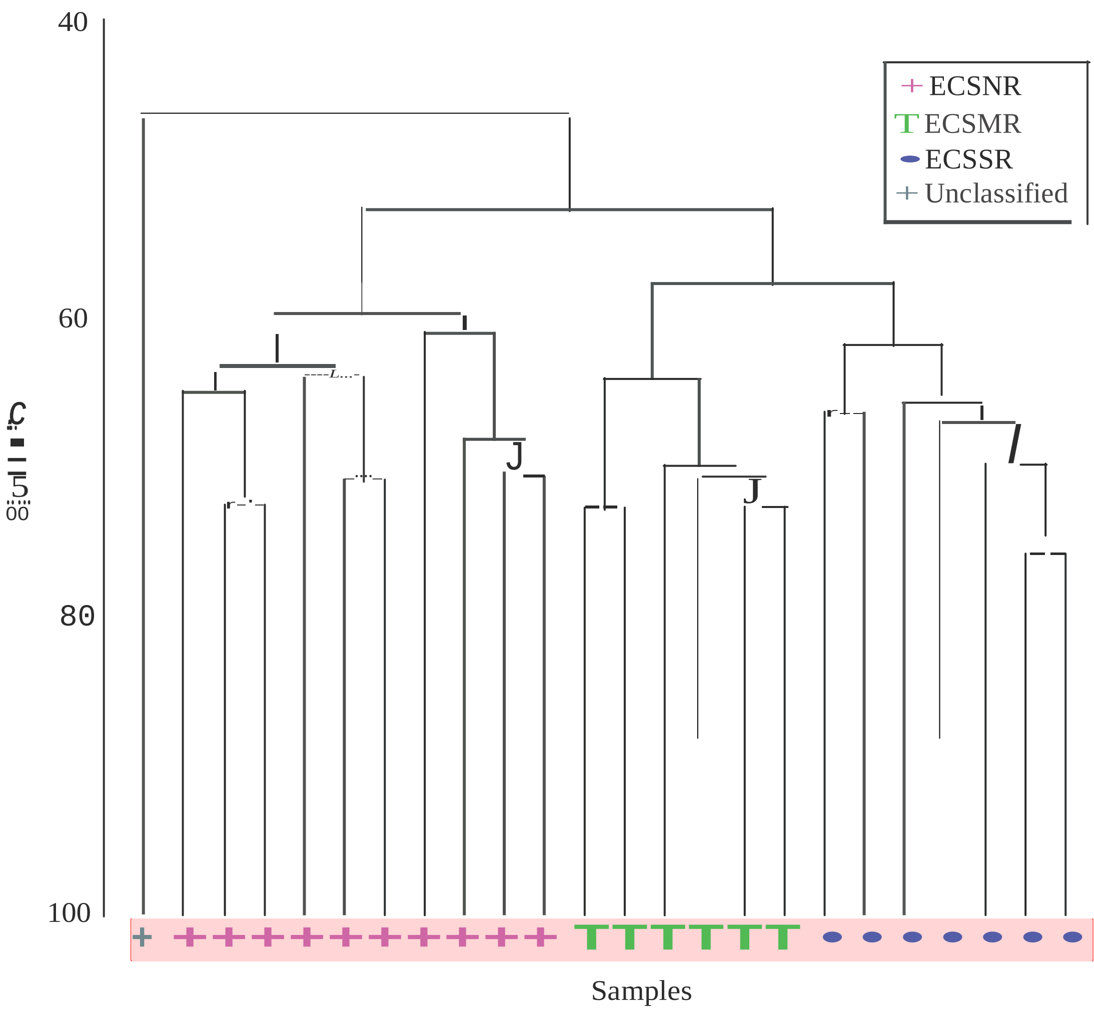


Figure 6

Cluster analysis of radiolarian assemblages in the ECSNR, ECSMR and ECSSR.



Comment [JR23]: Should add sample site names.

Figure 7

The redundancy analysis (RDA) ordination: (A) samples, (B) species.

Species codes: *DicPro* – *Dictyocoryne profunda*, *DidTet* – *Didymocyrtis tetrathalamus*, *PhoPyl* – *Phorticium pylonium*, *SpoTet* – *Spongaster tetras*, *SpoRes* – *Spongodiscus resurgens*, *StyMul* – *Stylodictya multispina*, *TetOct* – *Tetrapyle octacantha*, *ZygPis* – *Zygocircus piscicaudatus* (in alphabetical order).

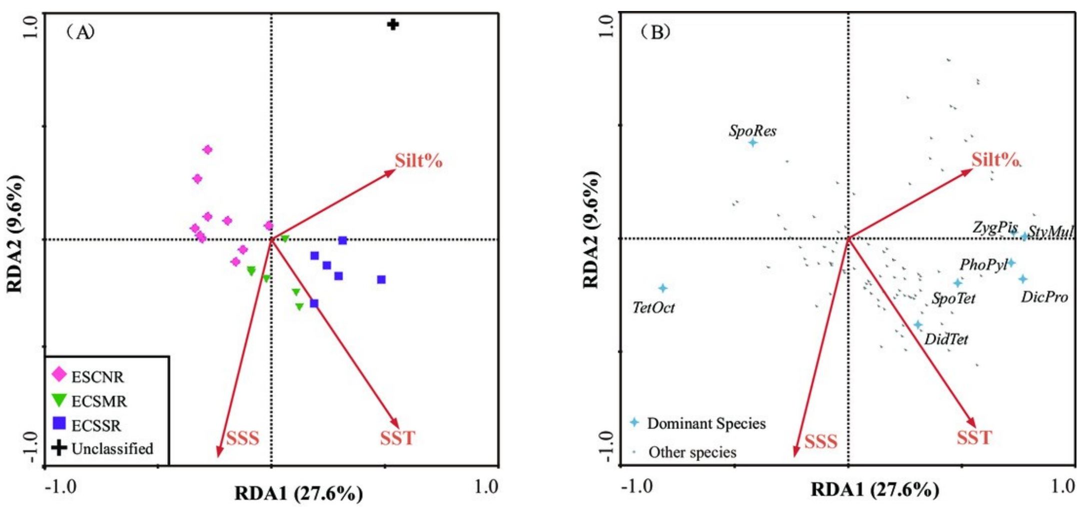


Figure 8

Comment [JR24]: Labels partially illegible

Distribution of the dominant radiolarian species, SST, and SSS in the ECSNR, ECSMR, ECSSR.

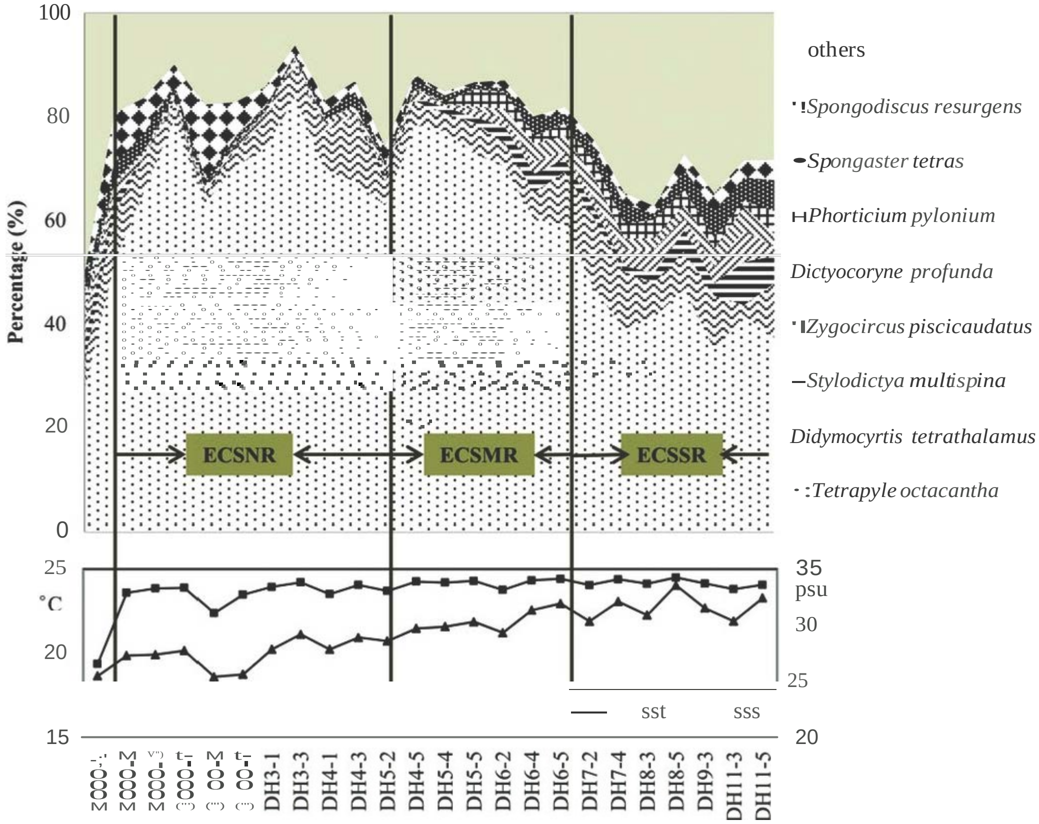


Figure 9

Radiolarian species observed in the surface sediment samples. Scale bar = 50 µm.

A. *Dictyocoryne profunda* Ehrenberg, 1860; B. *Didymocyrtis tetrathalamus* (Haeckel, 1887); C. *Phorticium pylonium* Haeckel, 1887; D. *Spongaster tetras* Ehrenberg, 1860; E. *Spongodiscus resurgens* Ehrenberg, 1854; F. *Stylodictya multispina* Haeckel, 1862; G-H, *Tetrapyle octacantha*.Mueller, 1858; I-J, *Zygocircus piscicaudatus* Popofsky 1913; K, *Stylochlamydium asteriscus* Haeckel, 1887; L. *Sethodiscus macrococcus* Haeckel, 1887; M. *Hexacontium pachydermum* Jorgensen, 1899; N, *Amphibrachium sponguroides* Haeckel, 1887; O, *Collosphaera huxleyi* Mueller, 1885; P-Q, *Rhizoplecta trithyris* Frenguelli, 1940; R, Acanthocorys castanoides Tan &Tchang, 1976; S, *Peromelissa spinosissima* Tan & Tchang, 1976; T, *Peridium* sp.; U. *Cycladophora bicornis* (Popofsky, 1908); V. *Helotholus histricosa* Jørgensen, 1905; W. *Phormospyris stabilis stabilis* (Goll, 1968); X. *Lithopera bacca* Ehrenberg, 1872; Y. *Lipmanella dictyoceras* (Haeckel, 1861).

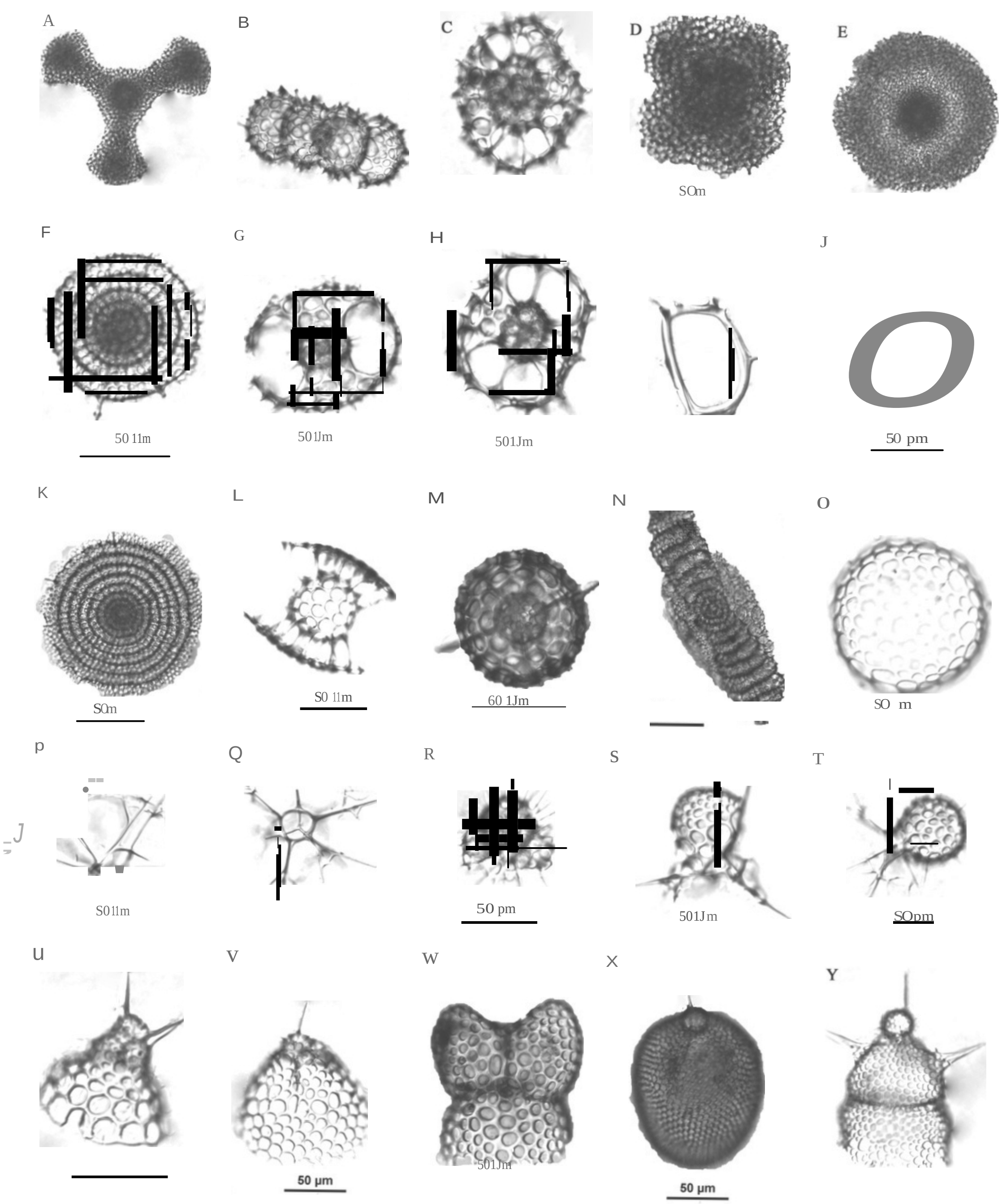

A
B
C
D
E
SOm
F
G
H
J
50 11m
501Jm
501Jm
50 pm
K
L
M
N
O
S0m
S0 11m
60 1Jm
SO m
p
Q
R
S
T
S011m
50 pm
501Jm
SOpm
u
V
W
X
Y
50 µm
501Jm
50 µm

Table 1(on next page)

The average values and standard errors (mean ± SE) of abundance and diversity indices in different regions (ECSNR, ECSMR, ECSSR)

Different lowercase a, b and c indicate significant differences among regional groups.

Abbreviations: *N*, Abundance (inds.$(100g)^{-1}$); *S*, number of species; *d*, Margalef's index; *J*', Pielou's index; *H*' ($\log_e$) , Shannon-Wiener's index; 1-*λ*', Simpson index.

Diversity index	ECSNR (n = 10)	ECSMR (n = 6)	ECSSR (n = 7)
N	911.70 ± 152.22[a]	2888.17 ± 522.66[b]	2724.86 ± 767.66[c]
S	22.50 ± 2.14[a]	38.16 ±1.40[b]	49.00 ± 5.34[b]
d	3.18 ± 0.24[a]	4.72 ± 0.18[b]	6.29 ± 0.64[b]
J'	0.44 ± 0.03[a]	0.43 ± 0.04[a]	0.70 ± 0.02[b]
H'	1.35 ± 0.10[a]	1.55 ± 0.16[b]	2.68 ± 0.08[c]
1-λ'	0.50 ± 0.04[a]	0.50 ± 0.06[a]	0.83 ± 0.01[b]

Table 2 (on next page)

Average relative abundance, contribution (%) and cumulative contribution (%) of the radiolarian fauna contributing to the similarity within each group. A cut-off at 50% similarity was employed.

Species	Av.Abund.	Contrib %	Cum %
ECSNR group	Average similarity: 61.96%		
Tetrapyle octacantha	65.31	42.60	42.6
Didymocyrtis tetrathalamus	5.97	10.15	52.75
Spongodiscus resurgens	5.32	9.13	61.88
ECSMR group	Average similarity: 67.15%		
Tetrapyle octacantha	68.73	31.79	31.79
Didymocyrtis tetrathalamus	5.54	8.23	40.02
Stylodictya multispina	1.88	4.17	44.19
Zygocircus piscicaudatus	1.4	4.08	48.27
Spongaster tetras	1.46	3.83	52.1
ECSSR group	Average similarity: 64.82%		
Tetrapyle octacantha	41.12	18.37	18.37
Didymocyrtis tetrathalamus	8.81	7.2	25.57
Spongaster tetras	3.84	4.91	30.47
Dictyocoryne profunda	3.11	4.66	35.13
Zygocircus piscicaudatus	3.29	4.47	39.6
Phorticium pylonium	2.88	4.35	43.96
Stylodictya multispina	3.51	4.21	48.16
Spongodiscus resurgens	2.62	4.15	52.31

Table 3(on next page)

Results of the RDA for the radiolarian assemblages and environmental variables, and conditional effects of the total environmental variables in the RDA with the significant variables in bold.

	Axes				Total Inertia
	1	2	3	4	
Eigenvalues	0.276	0.096	0.071	0.035	1
Species-environment correlations	0.967	0.938	0.919	0.806	
Cumulative percentage variance of species data	27.6	37.2	44.2	47.7	
Cumulative percentage variance of species-environment relation	52.4	70.5	83.9	90.5	
Sum of all eigenvalues					1
Sum of all canonical eigenvalues					0.527

	Conditional Effects				
Variable	VIF	LambdaA	% contribution to canonical eigenvalues	p	F
SST	2.55	0.14	27%	0.003	3.51
SSS	4.31	0.2	38%	0.001	5.81
Silt%	5.54	0.06	11%	0.013	1.99
Clay%	4.91	0.05	9%	0.068	1.55
Nitrate	5.58	0.04	8%	0.189	1.29
Phosphate	4.35	0.04	8%	0.118	1.41

Comment [JR25]: Values should be aligned with headings.

Table 4 (on next page)

The Spearman correlation between diversity indices and the environmental variables. Values of significant correlations ($p < 0.05$) are in bold.

Abbreviations: *N*, Abundance (inds.$(100g)^{-1}$); *S*, number of species; *d*, Margalef's index; *J*', Pielou's index; *H*' ($\log_e$) , Shannon-Wiener's index; 1-*λ*', Simpson index.

Diversity index	n	SST		SSS		Silt percentage	
		r	p	r	p	r	p
N	23	0.771	0.000	0.620	0.002	0.096	0.664
S	23	0.748	0.000	0.563	0.005	0.140	0.524
d	23	0.663	0.001	0.489	0.018	0.107	0.628
J'	23	0.289	0.182	-0.191	0.383	0.500	0.015
H'(log_e)	23	0.451	0.031	0.012	0.957	0.423	0.044
1 - λ'	23	0.304	0.158	-0.163	0.457	0.511	0.013