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The Southern Ocean RADiolarian (SO-RAD) dataset: a new compilation of modern radiolarian census data

Kelly-Anne Lawler[1], Giuseppe Cortese[2], Matthieu Civel-Mazens[3,4], Helen Bostock[5,6], Xavier Crosta[7], Amy Leventer[8], Vikki Lowe[5], John Rogers[1], Leanne K. Armand[1]

[1]Research School of Earth Sciences, The Australian National University, Canberra, ACT, 2601, Australia
[2]GNS Science, 1 Fairway Drive, Avalon, Lower Hutt 5010, New Zealand
[3]Graduate School of Integrated Arts and Sciences, Kochi University, Japan
[4]Geological Survey of Japan, AIST, Tsukuba, Japan
[5]School of Earth and Environmental Sciences, University of Queensland, Australia
[6] National Institute of Water and Atmospheric Research (NIWA), Wellington, New Zealand
[7]Université de Bordeaux, CNRS, EPHE, UMR 5805 EPOC, 33615 Pessac, France
[8]Geology Department, Colgate University, Hamilton NY, USA

Correspondence to: Kelly-Anne Lawler (kelly-anne.lawler@anu.edu.au)

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Abstract

Radiolarians (holoplanktonic Protozoa) preserved in marine sediments are commonly used as palaeoclimate proxies for reconstructing past Southern Ocean environments. Generating reconstructions of past climate based on microfossil abundances, such as radiolarians, requires a spatially and environmentally comprehensive reference dataset of modern census counts. The Southern Ocean RADiolarian (SO-RAD) dataset includes census counts for 238 radiolarian taxa from 228 surface sediment samples located in the Atlantic, Indian and southwest Pacific sectors of the Southern Ocean. This compilation is the largest radiolarian census dataset derived from surface sediment samples in the Southern Ocean. The SO-RAD dataset may be used as a reference dataset for palaeoceanographic reconstructions, or for studying modern radiolarian biogeography and species diversity. As well as describing the data collection and collation, we include recommendations and guidelines for cleaning and subsetting the data for users unfamiliar with the procedures typically used by the radiolarian community. The SO-RAD dataset is available to download from doi.pangaea.de/10.1594/PANGAEA.929903 (Lawler et al., 2021).

1 Introduction

The Southern Ocean is an important part of the global climate system as a major hub of oceanic circulation and nutrient redistribution. Future changes to its physical, chemical, and biological properties will therefore have global climate implications. Palaeoceanographic reconstructions of the Southern Ocean reveal its response to past climate forcings and help model how it might respond to these forcings in the future. Marine microfossils are commonly used as climate proxies to obtain such reconstructions (Yasuhara et al., 2020). Plankton distribution and abundance are related to the oceanic conditions prevalent in the water masses where these organisms live. After death, their skeletons settle to the ocean floor becoming part of the sedimentary record. In the southern hemisphere, subtropical to Antarctic ocean floor sediments are dominated by two siliceous microfossil groups, diatoms and radiolarians, which are used to determine past environmental conditions such as ocean temperature (Cortese and Abelmann, 2002; Panitz et al., 2015) and sea-ice coverage (Crosta et al., 2004; Ferry et al., 2015).

Radiolarians are unicellular, eukaryotic marine microzooplankton, generally ranging in size from 30 – 300 μm, that inhabit all depths throughout the world's oceans. Belonging to the supergroup Rhizaria, Radiolaria consist of 600-800 extant species in five orders: Acantharia, Taxopodia, and the siliceous polycystine orders Collodaria, Nassellaria and Spumellaria (Boltovskoy et al., 2017; Suzuki and Not, 2015). Radiolarians belonging to the polycystine orders are the most likely to be found in marine sediments and are therefore the focus of most micropaleontological studies, including this one. Radiolaria feed on diatoms, other small algae and bacteria, and some also have photosynthetic algal symbionts. Little is known about the radiolarian life cycle as they are notoriously difficult to culture (Lazarus, 2005; Suzuki and Not, 2015). In the Southern

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Ocean, radiolarian productivity is highest (up to 90% of annual flux) during the Austral summer (Abelmann, 1992; Abelmann and Gersonde, 1991). Moreover, unlike diatoms, radiolarians are not at their most abundant in the surface waters of the Southern Ocean, rather they peak in abundance between 100-400 m water depth south of 45°S (Abelmann and Gowing, 1997; Boltovskoy, 2017).

Fossil radiolarians are useful for paleoclimate reconstructions at high latitudes and in deep-sea regions where carbonate microfossils are generally not well preserved. In the future, the importance of siliceous microfossils may be even more pronounced due to ocean acidification and the corresponding decline in the abundance of carbonate-shelled plankton (Moy et al., 2009; Rigual Hernández et al., 2020). After diatoms, radiolarians are the second largest source of biogenic silica in marine sediments (Anderson, 2019). Fossil radiolarians have long been used as a palaeo-proxy for Southern Ocean sea-surface temperature (Lozano and Hays, 1976; Cortese and Abelmann, 2002; Cortese et al., 2007; Rogers and De Deckker, 2011; Panitz et al., 2015) and, more recently, have been used for reconstructing subsurface ocean temperature (Hernández-Almeida et al., 2020; Civel-Mazens et al., 2021). Such palaeoceanographic reconstructions rely on a spatially and environmentally comprehensive radiolarian reference dataset.

In this paper we present, for the first time, the Southern Ocean RADiolarian (SO-RAD) dataset consisting of census data for 238 radiolarian taxa from 228 surface sediment samples. We illustrate the spatial and environmental coverage the dataset provides, briefly describe the distribution and abundance of taxa within the dataset and discuss how the dataset might be cleaned and/or split into subsets prior to analysis. The SO-RAD dataset can be used as a reference dataset for proven palaeoceanographic reconstructions or to explore new parameters for estimation, as standalone data to assist studies in the biogeography and diversity of modern Southern Ocean radiolarian species, or for the development of new statistical methods in microfossil analysis.

2 Methods

2.1 Southern Ocean Radiolarian Dataset

The Southern Ocean Radiolarian (SO-RAD) dataset includes census counts for 238 taxa/taxonomic groups from 228 surface sediment samples located in Atlantic, Indian and southwest Pacific sectors of the Southern Ocean (Figure 1). This compilation is the largest dataset available for radiolarian-based palaeoenvironmental reconstructions constrained to the Southern Ocean. Sector-specific datasets have been previously published as follows: Atlantic sector (Abelmann et al., 1999; Cortese and Abelmann, 2002), southwest Pacific sector (Cortese and Prebble, 2015), and Indian sector (Rogers and De Deckker, 2007). These existing data, after a recount of the Indian sector sites to ensure taxonomic consistency, have been compiled as one dataset and expanded on by including census data from 25 previously unpublished sites in the Ross Sea, and the Indian sector of the Southern Ocean. Sediment coring in the Southern Ocean, particularly in areas close to the ice edge where sea-ice coverage varies from season to season, is expensive and difficult to plan. The SO-RAD dataset is, thus, the result of cooperative international partnerships based on decades of oceanographic voyages undertaken by scientists from

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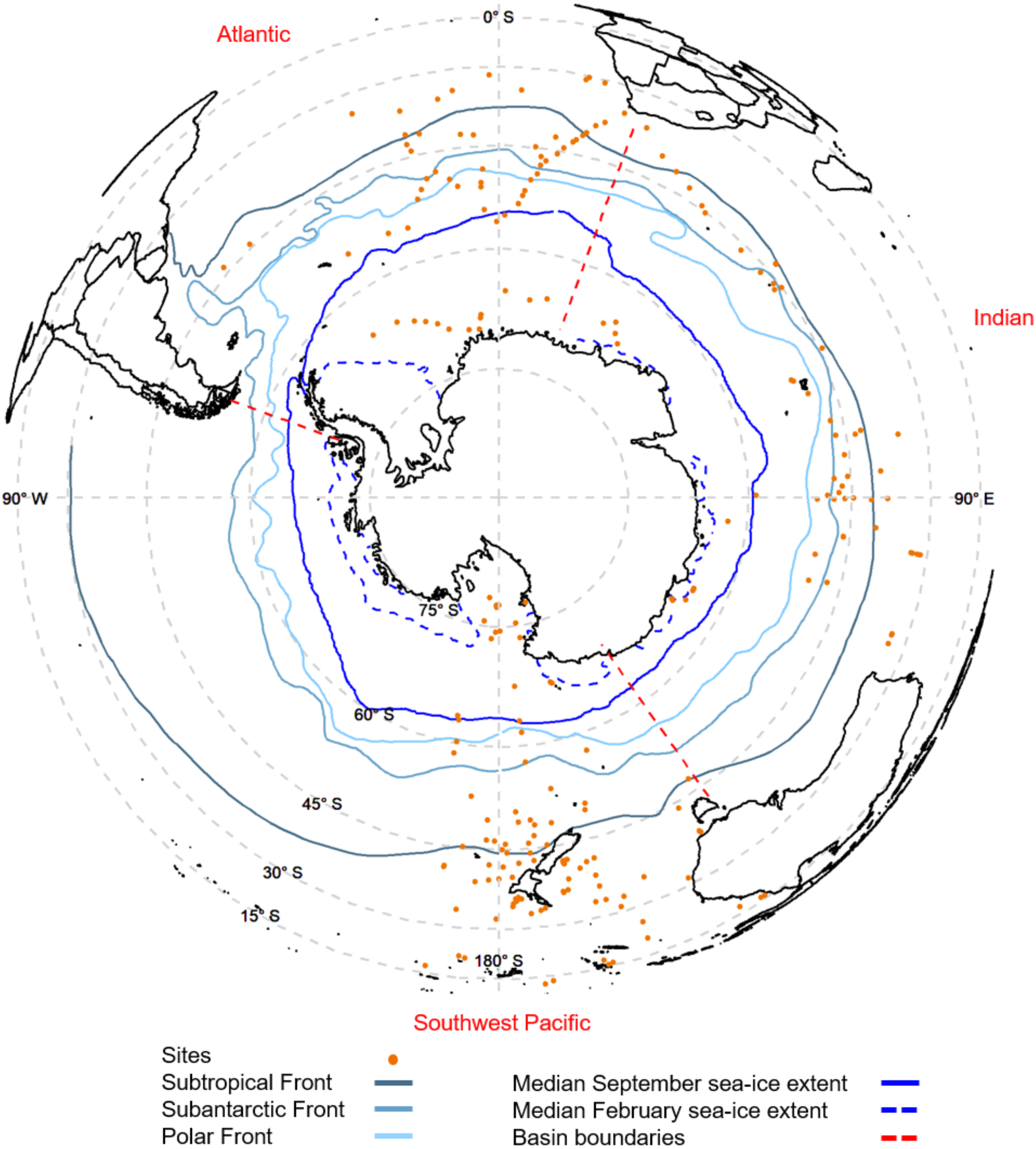

Figure 1: Surface sediment sites included in the SO-RAD database shown with a) Southern Ocean frontal boundaries (Orsi et al., 1995), and ocean basin boundaries (WOCE Data Products Committee, 2002), and b) the 1981 - 2010 median sea-ice extent for February (broken line) and September (solid line) (Fetterer et al., 2017).

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many institutions and nations. In a compilation such as the SO-RAD dataset, sample locations are not chosen according to uniform spatial coverage criteria, but rather dictated by the availability of, and access to, radiolarian-bearing surface sediment samples.

2.1.1 Census sources and handling protocols

In bringing together census data for this global dataset from various sources, the following data limitations and handling procedures are detailed.

Census data from the Atlantic sector include radiolarian counts from 64 sites. Data from 44 sites were published by Abelmann et al. (1999) and 20 sites were subsequently added and published in Cortese and Abelmann (2002). Sites from Abelmann et al. (1999) and Cortese and Abelmann (2002) do not include the full counts of all taxa observed at each site, rather they include only a selection of the taxa observed. Taxa were excluded from these sites prior to publication based on criteria outlined in Abelmann et al. (1999) such as their relative abundances (i.e., excluding rare taxa, with the threshold set at 2%), depth preferences, and clarity of identification. The percentage of the total radiolarian count included at each site is recorded in the SO-RAD dataset under the variable 'Perc'. These sites have been included in the dataset, despite containing counts for only a percentage of the taxa observed, because they contain valuable information about species useful for palaeo-reconstructions and for single-species studies.

Radiolarian census data from 102 sites located in the southwest Pacific sector include 88 sites published by Cortese and Prebble (2015). These data contained full census counts and required no further treatment.

The Indian Ocean sector includes census data from 40 sites first published by Rogers and De Deckker (2007). The slides from these sites were recounted to ensure consistency with the taxonomy of the SO-RAD compilation presented here (described in further detail in section 2.1.3). Also located in the Indian Ocean sector are census data from four sites from Abelmann et al. (1999) and six from Cortese and Abelmann (2002).

We also include radiolarian census data from 25 previously unpublished sites. These include counts from 14 archive samples from sites in the Ross Sea, retrieved during multiple expeditions by the National Institute of Water and Atmospheric Research (NIWA) and its predecessor New Zealand Oceanographic Institute; five sites near the Sabrina Coast, East Antarctica (three retrieved during the 2017 RV *Investigator* voyage IN2017-V01 (Armand et al., 2018), two during the 2014 RVIB *Nathaniel B. Palmer* voyage NBP-1402 (Leventer and Science Party, 2014); and a total of six samples retrieved during the MD185 INDIEN-SUD1 (Mazaud and Michel, 2011), MD189 INDIEN-SUD2 (Mazaud and Michel, 2012) and MD218 CROTALE (Crosta, 2019) voyages.

2.1.2 Slide preparation and microscopy

For both the previously published and unpublished sites, slides were prepared using the procedure described in Cortese and Prebble (2015). Sediment samples were dried, weighed, placed in beakers with 100mL of distilled water, and heated to 60-70°C on a hotplate. Organic matter was removed by adding a mixture of diluted hydrogen peroxide (ca. 20% concentration) and sodium hexametaphosphate (Calgon ™) and left to react for one hour. To remove carbonate, 10% hydrochloric acid was added to the beaker. On completion of the reaction, usually within ca. 30 minutes, the content of the beaker was washed over a 45µm mesh-size sieve. The hydrogen peroxide wash was repeated to ensure the sample was completely disaggregated. The residue was placed in a beaker or storage bottle with distilled water, stirred into suspension, and a pipette used to place a few drops of it on a coverslip. Once the latter dried up on a hotplate, it was mounted on a slide by using Canada balsam or Norland™ Optical Adhesive (NOA61) as a mounting medium. Finally, the mounted slide was either placed on a hotplate again for ca. 10-20 minutes to allow the Canada balsam to harden, or under ultraviolet light for the NOA61 to cure. Radiolarian census counts were determined using transmitted-light microscopy at 100-400x magnification. The number of individuals counted per site ranges from 44 to 706, with a median of 381.

2.1.3 Taxonomy

Species identification is mainly based on the taxonomic concepts of Petrushevskaya (1967, 1971), Nigrini and Moore (1979) and Boltovskoy (1998). This was supplemented by consulting Lazarus et al. (2015), the online dataset at www.radiolaria.org, (Radiolaria.org, n.d.) with a final check on currently valid taxonomic concepts according to the World Register of Marine Species (WoRMS Editorial Board, 2020). Some naming adjustments were made to taxa in the previously published datasets where more recent, accepted names were available. If individuals could not be identified at species level, they were assigned to a higher rank taxonomic group e.g., from genus level identifications to those identified only as belonging to the Nassellaria or Spumellaria orders.

A total of 238 radiolarian taxa have been recognised. Radiolarian taxa identified in SO-RAD are from the super-class Polycystinea, which is divided into three orders, Nassellaria, Spumellaria and Collodaria. When present, phaeodarian species were identified, counted, and recorded. The binomial names for each of the taxa included in the SO-RAD dataset are listed in Supplement 1.

2.2 Complementary Data

To spatially categorise the dataset, each site was assigned to one of four zones: the Antarctic Zone (AZ; south of the Antarctic Polar Front), Polar Frontal Zone (PFZ; between the Polar and Subantarctic Fronts), Subantarctic Zone (SAZ; between the Subantarctic and Subtropical Fronts), or Subtropical Zone (STZ; north of the Subtropical Front), based on frontal boundaries delineated by Orsi et al., (1995). Sites were also assigned to one of three sectors, either the Atlantic,

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Indian or southwest Pacific sector, based on the longitudinal boundaries used by the World Ocean Circulation Experiment (WOCE Data Products Committee, 2002).
To illustrate the environmental coverage of the dataset, Austral summer (January - March) observations of temperature (°C), salinity(psu), and dissolved oxygen (µmol/kg), silicate (µmol/kg), nitrate (µmol/kg) and phosphate (µmol/kg), were extracted from the World Ocean Atlas 2018 (Garcia et al., 2019a, 2019b; Locarnini et al., 2018; Zweng et al., 2019) using Ocean Data View software (Schlitzer, 2020). These data represent a collation of 1°x1° gridded data from 1955 – 2017 and, given that radiolarian abundances are highest below the surface, we elected to use data reported at 100 m depth. The median sea-ice extent boundaries from 1981 – 2010 representing minimum (February) and maximum (September) sea-ice extents were retrieved from the National Snow and Ice Data Center repository (Fetterer et al., 2017). These monthly sea-ice extent boundaries are based on >15% sea-ice concentration.

2.3 Structure of the SO-RAD dataset

The SO-RAD dataset consists of 228 rows (plus a header row) and 252 columns. Each row contains data for one site from which a surface sediment sample was obtained. Columns 1-14 contain information relating to the site or sample, while columns 14 - 252 are the radiolarian taxa observed (one taxon per column).

Table 1: Description of variables in the SO-RAD dataset

Column and variable name	Description
Event	The sampling site/station at which the data was obtained.
Campaign	The name of the cruise/expedition/leg during which the sample was collected.
Site	Site names act as unique identifier for each record (row).
Latitude	All latitudes are negative as all sites are in the southern hemisphere. Units are decimal degrees.
Longitude	Western hemisphere longitudes are negative (e.g., 155°00'W = -155.00) Units are decimal degrees.
Zone	The location of the site according to the boundaries described in section 2.2. AZ = Antarctic Zone PFZ = Polar Frontal Zone SAZ = Subantarctic Zone STZ = Subtropical Zone
Sector	The location of the site according to the boundaries described in section 2.2. ATL = Atlantic sector IND = Indian sector

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	SWP = Southwest Pacific sector
Bathy Depth	Bathymetric depth i.e., depth below sea level. Units are metres.
Sample method	The method used to extract the sediment core/sample from the seafloor.
Depth top	The upper depth of the sample. Units are metres.
Depth bot	The lower depth of the sample. Units are metres.
Depth	The average of the upper and lower depth of the sample. Units are metres.
Rad	The number of individual radiolarians observed in each sample. This data can be used to convert counts to relative abundance.
Perc	The percentage of the total count included. This variable is always 100, except for the sites where only a portion of the taxonomic counts were available to us. Units are percentages expressed as a decimal rounded to 2 decimal places.
Radiolarian taxa	Columns 15 - 251 contain census data for each taxonomic grouping in the dataset. Units are the number of individuals observed in a sample.

2.4 Software

All figures and summary statistics in this paper were generated using R statistical software (R core team, 2020) and the packages *mapproj* (McIlroy, 2020), *maps* (Becker, 2018), *orsifronts* (Sumner, 2015), *rgdal* (Bivand et al., 2020) and *tidyverse* (Wickham et al., 2019).

3 Results

3.1 Spatial distribution of data

The SO-RAD dataset is the most comprehensive Southern Ocean radiolarian surface sediment dataset available however, the spatial coverage is uneven with, for example, more Antarctic Zone sites in the Atlantic sector than in the Indian and southwest Pacific sectors, and more Subtropical Zone sites in the southwest Pacific sector (Table 2). The latter sector has better overall coverage than the Atlantic and Indian sectors, nevertheless there is a paucity of sites from the Pacific Ocean east of the Ross Sea. Sites represent locations covering a large water depth gradient, from the Antarctic continental shelf (235 metres below sea level) to the abyssal plain (5883 metres below sea level).

3.2 Environmental distribution/coverage of data

Sites included in the SO-RAD dataset are representative of a broad range of environmental conditions. Temperature values range from -1.8°C to 26.4°C, salinity from 33.8 to 35.7 psu, and dissolved oxygen from 180.3 to 337.9 µmol/kg. The SO-

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RAD dataset also includes sites representing a large range of nutrient concentrations: nitrate (0.1 - 31.4 µmol/kg), phosphate (0.1 - 2.2 µmol/kg) and silicate (0.6 - 89.3 µmol/kg) (Figures 2 and 3). Forty-three sites lie on, or within, the median September sea-ice extent boundary, however no sites lie within the median February sea-ice extent boundary. Some sites are to the north of the median September sea-ice extent boundary and may be affected by sea ice in certain years, however, the remainder are well removed from the direct influence of seasonal sea ice.

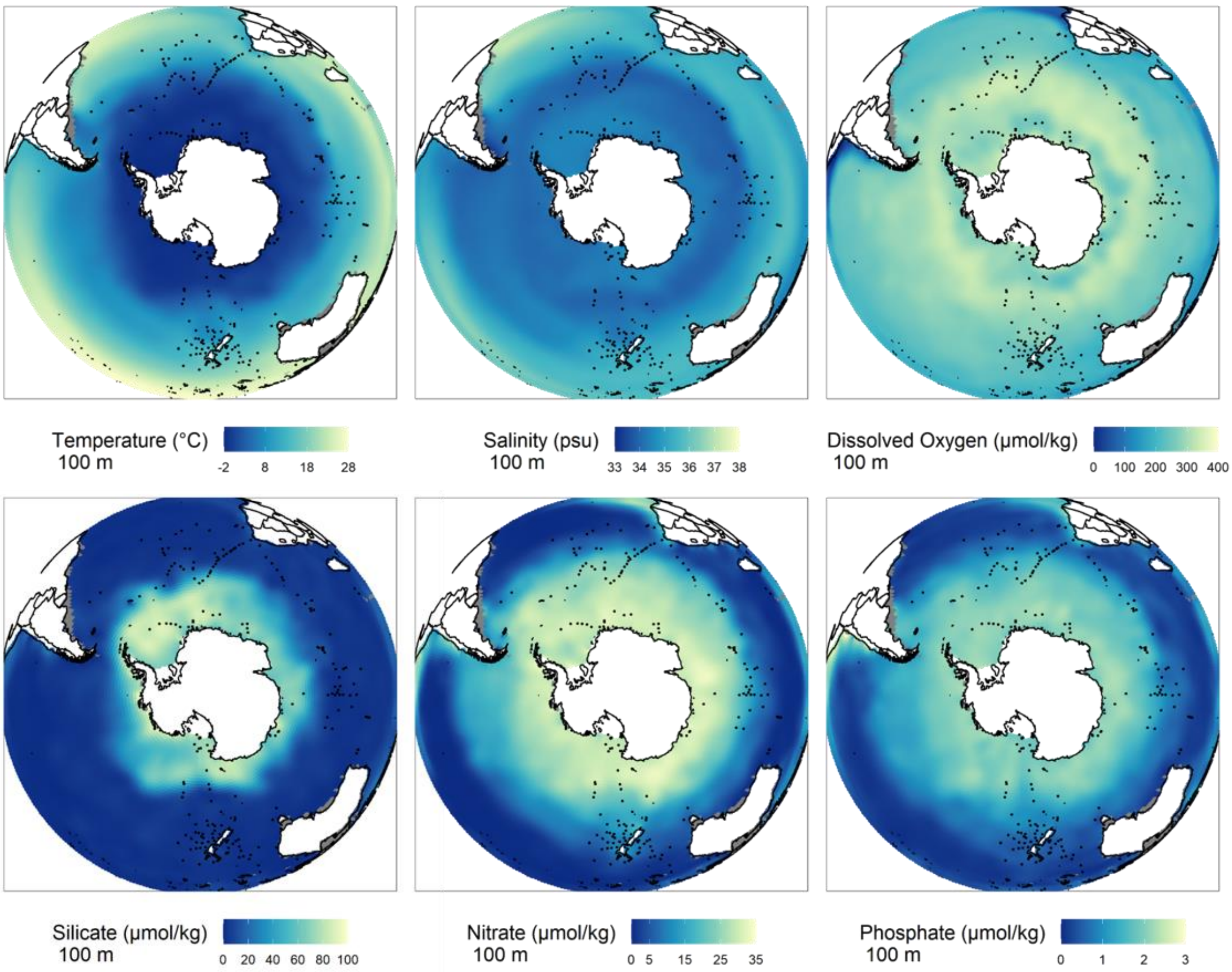

Figure 2: Locations of sites (black dots) and the six environmental variables at 100 m water depth used to demonstrate the environmental coverage of the SO-RAD dataset (Data source: Garcia et al., 2019a, 2019b; Locarnini et al., 2018; Zweng et al., 2019).

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Table 2: Number of sites located in each zone and sector of the Southern Ocean.

	Atlantic Sector	Indian Sector	Southwest Pacific Sector	Total sites per zone
Subtropical/Tropical Zone	14	13	58	85
Subantarctic Zone	17	26	21	64
Polar Frontal Zone	7	9	5	21
Antarctic Zone	26	14	18	58
Total sites per sector	64	62	102	228

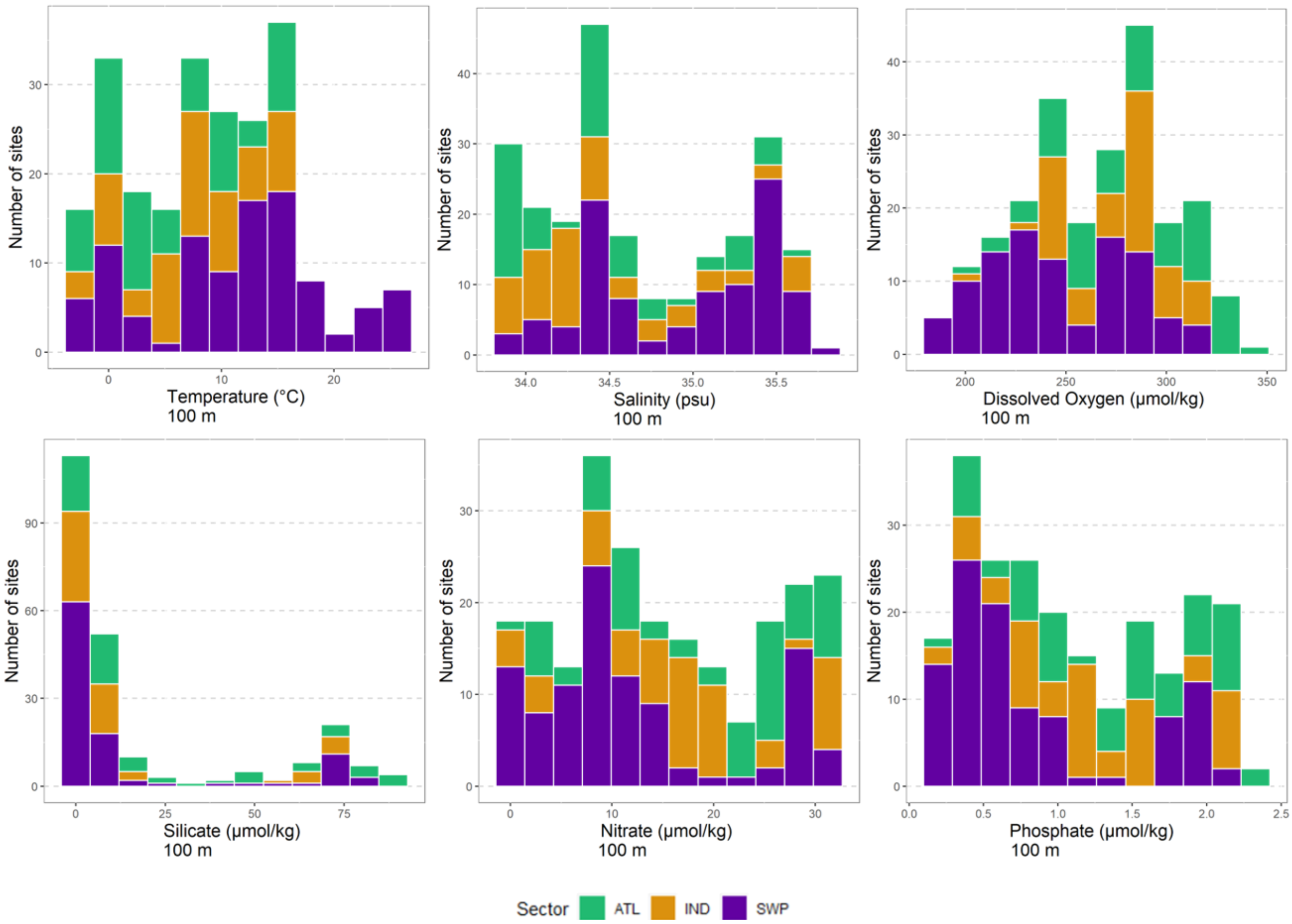

Figure 3: Distribution of sites across observed environmental variables at 100 m water depth (Garcia et al., 2019a, 2019b; Locarnini et al., 2018; Zweng et al., 2019) identified by sector – Atlantic Ocean sector (ATL), Indian Ocean sector (IND), southwest Pacific sector (SWP).

3.3 Radiolarian distribution and abundance

The SO-RAD dataset documents 238 identified taxa characterised by subspecies/species level identifications through to individuals identified only as belonging to the Nassellaria or Spumellaria orders.

Radiolarian species (i.e., not including taxa of genus level and above, or taxa that had not been formally described) with the highest average relative abundances were *Antarctissa denticulata* and *Antarctissa strelkovi*. These were the only species with average relative abundances >10%. The *Antarctissa* genus (consisting of *A. denticulata*, *A. strelkovi* and *Antarctissa* spp.) is the most abundant radiolarian genus in the Southern Ocean and was observed at 146 sites. It has a relative abundance of >40% at several sites in the SO-RAD dataset (n=29), with some sites in the Ross Sea consisting of >80% *Antarctissa* species.

Other well-distributed and abundant species were *Tetrapyle octacantha/stenozona* (average relative abundance = 4.3%, observed at 161 sites), *Cenosphaera cristata* (3.75%, 123 sites), *Cycladophora bicornis* (3.72%, 165 sites), *Lithomelissa setosa* (3.52%, 77 sites), *Lithomelissa* sp. A (3.4%, 95 sites), *Phorticium clevei* (3.24%, 129 sites) and *Lithelius minor* (3.19%, 170 sites) (Figure 4). Only one other species, *Sphaerozoum punctatum* (3.28%), had an average relative abundance > 3%, however it was observed at only 9 sites.

Thirty-eight taxa were found at more than 100 sites. *Spongopyle osculosa* was the most widely distributed species having been observed at 200 sites.

There were 71 taxa (30% of the total number of taxa) in the SO-RAD dataset considered to be ‘rare’ i.e., they had a maximum relative abundance <1% and/or were observed at only one site. If the maximum relative abundance threshold for a rare categorisation was increased to <2%, then 123 taxa (52%) would be considered rare.

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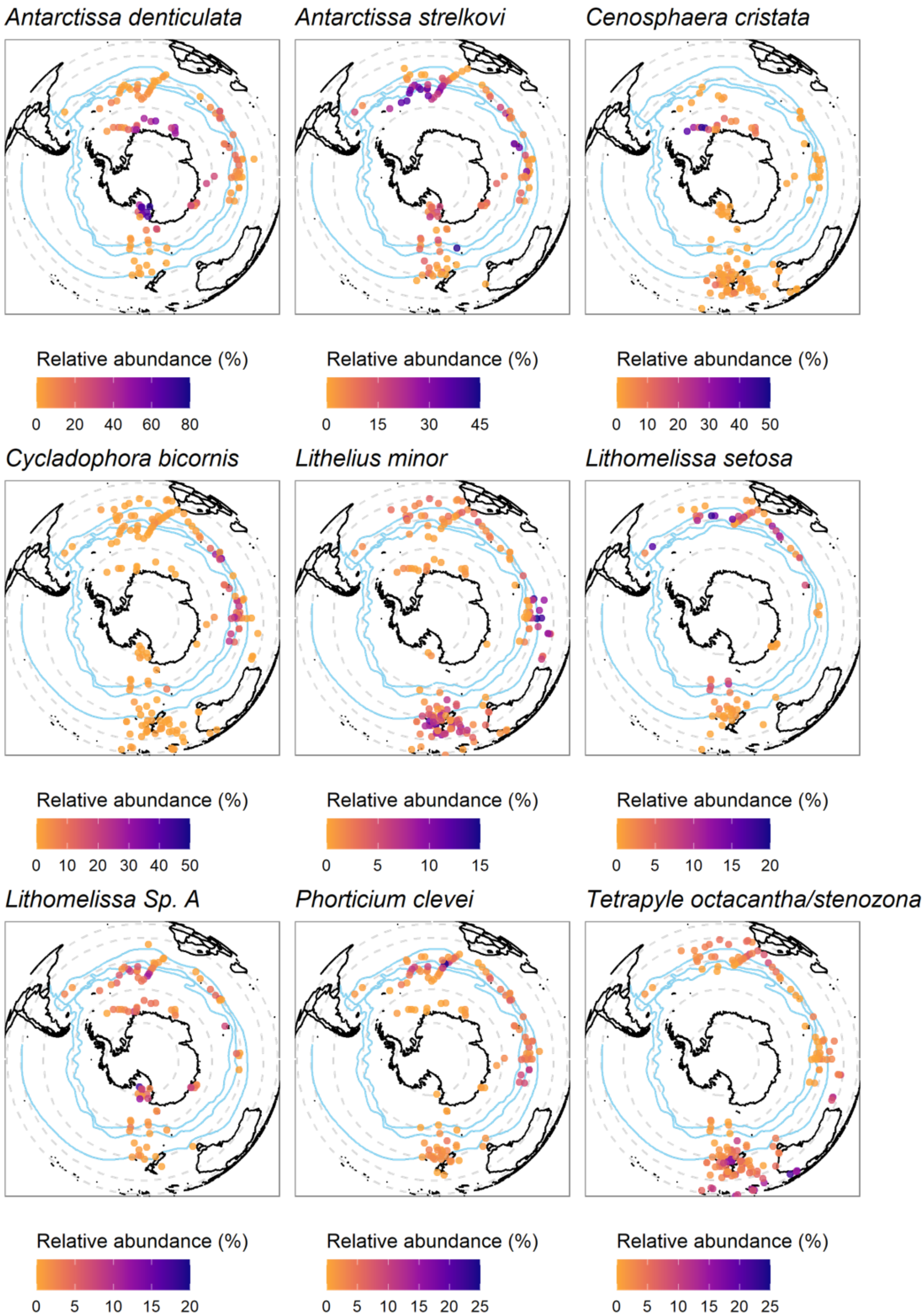

220 **Figure 4**: Distribution maps for the nine most abundant and widely distributed radiolarian taxa.

4 Discussion

While the SO-RAD dataset is predominantly a Southern Ocean dataset, there are several sites located considerably north of the Subtropical Front (the northern boundary of the Southern Ocean). One of the anticipated uses of the SO-RAD dataset is as a reference dataset for radiolarian-based palaeoenvironmental reconstructions from sediment cores retrieved from the Southern Ocean and Subtropical southern hemisphere. One of the key requirements of a reference dataset is that it should cover a wide range of environmental conditions, hence the inclusion of sites as far north as 11°S. It has been demonstrated elsewhere that radiolarian assemblages from temperate latitudes, such as offshore New Zealand, show large and distinct changes over glacial and interglacial periods (e.g., Lüer et al., 2009). Proving context from the SO-RAD modern reference dataset, with coverage extending from equatorial to truly polar conditions, facilitates positioning future faunal shifts, and imparts robustness to the environmental variable estimates derived from them. In a broader sense, the large spatial and environmental coverage of this dataset can aid in the refining of palaeoenvironmental reconstructions using radiolarian assemblages from periods that were substantially cooler or warmer than the present. Granting the SO-RAD dataset's significance to palaeoceanography and palaeoclimatology, the database is a valuable resource for exploring how physical, biological, and chemical characteristics of the Southern Ocean influence modern radiolarian biogeography, ecology, and species diversity. The SO-RAD dataset also holds potential for the exploration of sea ice coverage/concentration as a causal mechanism underlying the abundance patterns for some of the species occurring in this region, with a view to establish surface-dwelling radiolarian species as sea-ice proxies, as routinely done for diatom species, such as *Fragilariopsis curta/cylindrus* and *F. obliquecostata* (Gersonde and Zielinski, 2000; Armand et al., 2005), and in diatom-based transfer functions (Crosta et al., 1998; Esper and Gersonde, 2014; Ferry et al., 2015). Radiolarian species inhabiting sub-surface and intermediate depths may be affected by sea-ice related changes deep in the water column, such as salinity and stratification changes due to brine rejection during sea-ice formation and may thus also act as a palaeo-indicator of past sea-ice presence.

4.1 General limitations of microfossils reference datasets

When constructing any reference dataset based on surface sediment samples there are possible sources of error and assumptions that apply. Reproducibility of species abundance data can be affected by differing taxonomic concepts held by the analysts. We have minimized this potential source of error by including counts by radiolarists who regularly collaborate on taxonomic concepts. Furthermore, the vast majority of the samples included here have been counted by only one of us. As more samples are added to the SO-RAD dataset, only samples for which quality control of the census data is possible, will be included in the database in an effort to further minimise this source of error.

The species-level taxonomy of all microfossil groups has been based on phenotype/morphology, and not on molecular biology. Identification can be difficult when there are only minor differences in morphology between species, or where there are fragments of an individual, or additionally, where a juvenile specimen has been encountered. Such instances exemplify

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the consistent use by us of assignment to higher rank taxonomic categories i.e., genus or family rather than species or subspecies.

When using surface sediment samples as a modern analogue record it is assumed that the fossil assemblages found within those sediments were representative of modern assemblages that lived in the water column above. This is problematic for two reasons. The first is that the coring device can affect the quality/age of the surface sediment sample. For example, using a multi-corer allows for easier observation, and intact retrieval of, the surface sediment/bottom water interface (Barnett et al., 1986). With other coring devices it is not possible to observe if the uppermost sediment layer is the true surface sediment sample, or if the top of the coring device was buried beneath the surface. This means the 'core top' sample may be from several centimetres below the surface and is not the most recently deposited sediment. Secondly, even when the sediment sample is truly from the surface, the transportation or reworking of sediment, or preferential dissolution of species, mean that the assemblages observed in the sediment may not be truly representative of the assemblages that lived in the water column above.

4.2 Cleaning and subsetting the SO-RAD dataset based on sites

Where possible, we have presented census counts in their complete form to cater for a variety of analyses as well as the development of novel techniques for radiolarian data analysis. We have opted not to present a 'reconstruction ready' dataset as we believe the full dataset is useful for more than just palaeoenvironmental reconstructions. However, for most analyses the dataset would not be used in its raw form. Here we offer practical suggestions for preparing and producing a subset from this dataset based on practices utilised by radiolarists in the past.

4.2.1 Quality control of sites

Users of the dataset may wish to extract a subset of the SO-RAD dataset based on sites for quality control reasons. For example, placing a lower bound on the total number of individuals counted per site may depend on which species are of interest to the user. In general, lower total counts are sufficient when only the dominant species will be used in the analysis, while higher total counts are needed when a user is interested in species comprising as little as 1% of the population. For example, there is a 30% probability of failing to observe a species that comprises 1% of the population when counting 100 individuals but, by increasing the count to 300 individuals, this probability is reduced to less than 1% (Fatela and Taborda, 2002).

Sites in the Atlantic sector, as well as some in the Indian sector, did not have full census counts available. Rules for the exclusion of species at these sites can be found in Abelmann et al. (1999). The percentage of the assemblage included in the SO-RAD dataset is listed in the 'Perc' column. For analyses requiring the inclusion of rare species, the sites with < 100% of the assemblage included may need to be removed prior to analysis.

The coring apparatus used to retrieve the core can affect the quality of the sample collected, and subsequently the age of the sample. Where known, the apparatus used to retrieve the core has been listed in the 'Sample Method' column to facilitate the extraction of a data subset based on this variable.

4.2.2 Ensuring spatial/environmental coverage is suitable

Palaeoenvironmental reconstructions require a reference dataset that provides appropriate spatial and environmental coverage. When using the SO-RAD dataset as a reference dataset for such reconstructions, a user may consider the location and environmental characteristics of individual sites and subset the data accordingly. Reference sites may be included based on regional needs e.g., by defining latitudinal and/or longitudinal boundaries, or by selecting sites based on sector or oceanographic zone. When known, probable glacial/interglacial upper/lower limits of the variable being reconstructed should be taken into consideration when subsetting by the observed modern values of the variable.

4.3 Cleaning and subsetting the SO-RAD dataset based on taxa

Here we outline some practices to consider when refining the SO-RAD dataset for use as a reference dataset in palaeoceanographic reconstructions. These include selecting only taxa that can be clearly identified and with clear taxonomic descriptions, selecting appropriate taxa for the depth level of the reconstruction, grouping species/subspecies with similar environmental affinities into higher-order groupings, and removing rare species.

4.3.1 Removing questionable taxonomic groupings

If the focus of a study is on environmental reconstructions, the signal-to-noise ratio in radiolarian census data can be increased by removing broad, often higher order, counting categories having no clear taxonomic boundaries/definitions, and hence questionable environmental significance. The inclusion of unidentifiable individuals in higher-order taxonomic groupings ensures the correct calculation of species relative abundances, however these taxa are not useful for analyses that rely on genus- or species-level data.

Broad, higher-order categories that can be taken into consideration for removal from the SO-RAD dataset prior to analysis, include the indeterminate Nassellaria and Spumellaria taxonomic groups, along with taxa including, but not necessarily limited to, Litheliidae/Pyloniidae, *Spongotrochus/Spongopyle* sp., Trissocyclidae, and *Zygocircus productus* group.

Some Phaeodarea taxa have been included in the census counts. Studies focusing only on Polycystine radiolarians should remove the Phaeodarians *Lirella melo*, and all species belonging to the genera *Euphysetta* and *Protocystis*.

4.3.2 Grouping taxa

Radiolarian reference datasets often contain taxonomic groupings made up of species/subspecies grouped at genus level, or of unrelated species with the same environmental affinities that may be routinely confused for one another during the counting procedure (e.g., Cortese and Prebble, 2015; Matsuzaki and Itaki, 2017). Grouping species is especially relevant for less abundant taxa, and for those with a particularly complex taxonomy. Grouping species and/or subspecies that have similar distributions according to water column and modern sediment sampling can increase the statistical weight (and thus their chances of inclusion in a working reference dataset) of rare species that are known to carry a strong environmental signal. For example, Collosphaeridae is a taxonomic group that can be composed of several to tens of species that are most abundant at low latitudes (Cortese & Prebble, 2015; Biard et al., 2016). At high latitudes, their presence alone, even in very small numbers, may be indicative of warmer than usual conditions. It is, therefore, useful to group these rare species so that their signal is not lost if removing rare species prior to analysis. Grouping species, while obviously leading to the loss of species-level information, also increases inter-comparability of results between different researchers/teams, as higher-level categories are generally more accommodating and less prone to identification mistakes based on fine skeletal differences. Recommended groupings are listed in Supplement 2 and are adapted from Cortese and Prebble (2015).

4.3.3 Removing rare taxa

Previous radiolarian-based palaeoenvironmental reconstructions and biogeographical studies have removed rare taxa using one, or both, of the following methods 1) removing species observed at fewer than a certain number of sites (e.g., Abelmann et al., 1999; Boltovskoy & Correa, 2016) and/or 2) removing species based on their abundances. In the latter situation, species were removed from previous datasets when their maximum relative abundance did not exceed 1% (Boltovskoy, 1987; Cortese & Prebble, 2015), 2% (Lozano & Hays, 1976; Abelmann et al., 1999), or had fewer than a certain number of individuals (Rogers & De Deckker, 2007). Conversely, some studies (e.g. Hernández-Almeida et al., 2020) elect not to remove rare species.

4.3.4 Removing taxa that do not inhabit the depth being reconstructed

As radiolarians are present throughout the water column, a surface sediment sample contains a collection of taxa that, while living, do not inhabit the same depth, but eventually end up in the same surface sediment sample. It may be desirable to limit the reference dataset to taxa that are known to live at the depth for which a specific environmental variable is being reconstructed. Examples of studies where the authors have used a subset of taxa based on their vertical distributions include Abelmann et al. (1999), Cortese and Abelmann (2002), and Matsuzaki and Itaki (2017).

4.4 Update strategy and future plans for the SO-RAD dataset

There are noticeable gaps in the spatial coverage of the SO-RAD dataset, in particular the area between the Ross Sea and the Antarctic Peninsula, comprising a vast part of the high-latitude south Pacific Ocean, and between Australia and the Antarctic continent in the Indian Ocean. The intention of the authors is that the SO-RAD dataset will be constantly evolving as more surface sediment samples, collected during upcoming oceanographic expeditions, become available for census counts.

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5 Data Availability

The SO-RAD dataset is available to download from doi.pangaea.de/10.1594/PANGAEA.929903 (Lawler et al., 2021).

6 Conclusion

The SO-RAD dataset contains census data for 238 radiolarian taxa from 228 Southern Ocean sites. The dataset is the most comprehensive Southern Ocean radiolarian census dataset to date. We have provided a detailed description of the methods used to build the dataset, along with an overview of the spatial and taxonomic coverage of the data. The SO-RAD dataset may be used as a reference dataset for palaeoenvironmental reconstructions, or in studies of modern radiolarian biogeography, ecology and species diversity.

7 Appendices

1: List of radiolarian taxa included in the SO-RAD dataset.

2: Recommended taxonomic groupings to simplify/harmonise the dataset.

8 Author Contribution

K-AL was responsible for the data curation (along with GC), formal analysis, investigation (along with GC and MC-M), data visualisation and preparation of the original draft. GC conceptualised and acquired funding for this study. Resources (access to samples) was provided by GC, HB, XC, AL, JR and LKA. GC and LKA supervised this project. All authors contributed to the review and editing of the manuscript.

9 Competing Interests

The authors declare that they have no conflict of interest.

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https://doi.org/10.5194/essd-2021-148
Preprint. Discussion started: 30 June 2021

References

Abelmann, A.: Radiolarian flux in Antarctic waters (Drake Passage, Powell Basin, Bransfield Strait), Polar Biol., 12(3), 357–372, https://doi.org/10.1007/BF00243107, 1992.

Abelmann, A. and Gersonde, R.: Biosiliceous particle flux in the Southern Ocean, Mar. Chem., 35(1–4), 503–536, https://doi.org/10.1016/S0304-4203(09)90040-8, 1991.

Abelmann, A. and Gowing, M. M.: Spatial distribution pattern of living polycystine radiolarian taxa - baseline study for paleoenvironmental reconstructions in the Southern Ocean (Atlantic sector), Mar. Micropaleontol., 30, 3–28, 1997.

Abelmann, A., Brathauer, U., Gersonde, R., Sieger, R. and Zielinski, U.: Radiolarian-based transfer function for the estimation of sea surface temperatures in the Southern Ocean (Atlantic Sector), Paleoceanography, 14(3), 410–421, https://doi.org/10.1029/1998PA900024, 1999.

Anderson, O. R.: Protozoa, Radiolarians, in Encyclopedia of Ocean Sciences: A Derivative of the Encyclopedia of Ocean Sciences, vol. 4, pp. 651–655, Elsevier Science & Technology, , 2019.

Armand, L., O'Brien, P and Science Party.: Post-survey report: Interactions of the Totten Glacier with the Southern Ocean through multiple glacial cycles (IN2017-V01)., , https://doi.org/10.4225/13/5acea64c48693, 2018.

Armand, L. K., Crosta, X., Romero, O. and Pichon, J.-J.: The biogeography of major diatom taxa in Southern Ocean sediments 1. Sea ice related species, Palaeogeogr. Palaeoclimatol. Palaeoecol., 223(1–2), 93–126, https://doi.org/10.1016/j.palaeo.2005.02.015, 2005.

Barnett, P. R. O., Watson, J. and Connelly, D.: A multiple corer for taking virtually undisturbed samples from shelf, bathyal and abyssal sediments, Proc. R. Soc. Edinb. Sect. B Biol. Sci., 88, 304–305, https://doi.org/10.1017/S0269727000014846, 1986.

Becker, R. A., Wilks, A. R., Brownrigg, R., Minka, T. P. and Deckmyn, A.: maps: Draw Geographical Maps. https://CRAN.R-project.org/package=maps, 2018.

Biard, T., Stemmann, L., Picheral, M., Mayot, N., Vandromme, P., Hauss, H., Gorsky, G., Guidi, L., Kiko, R. and Not, F.: In situ imaging reveals the biomass of giant protists in the global ocean, Nature, 532(7600), 504–507, https://doi.org/10.1038/nature17652, 2016.

Bivand, R., Keitt, T. and Rowlingson, B.: rgdal: Bindings for the "Geospatial" Data Abstraction Library. https://CRAN.R-project.org/package=rgdal, 2020.

Boltovskoy, D.: Sedimentary Record of Radiolarian Biogeography in the Equatorial to Antarctic Western Pacific Ocean, Micropaleontology, 33(3), 267–281, https://doi.org/10.2307/1485643, 1987.

Boltovskoy, D.: Classification and distribution of South Atlantic Recent polycystine Radiolaria, Palaeontol. Electron., https://doi.org/10.26879/98006, 1998.

Boltovskoy, D.: Vertical distribution patterns of Radiolaria Polycystina (Protista) in the World Ocean: living ranges, isothermal submersion and settling shells, J. Plankton Res., 39(2), 330–349, https://doi.org/10.1093/plankt/fbx003, 2017.

https://doi.org/10.5194/essd-2021-148
Preprint. Discussion started: 30 June 2021

Boltovskoy, D. and Correa, N.: Biogeography of Radiolaria Polycystina (Protista) in the World Ocean, Progress in Oceanography, 149, 82–105, https://doi.org/10.1016/j.pocean.2016.09.006, 2016.

Boltovskoy, D., Anderson, O. R. and Correa, N. M.: Radiolaria and Phaeodaria, in Handbook of the Protists, edited by J. M. Archibald, A. G. B. Simpson, C. H. Slamovits, L. Margulis, M. Melkonian, D. J. Chapman, and J. O. Corliss, pp. 1–33, Springer International Publishing, Cham, https://doi.org/10.1007/978-3-319-32669-6_19-2, , 2017.

Civel-Mazens, M., Crosta, X., Cortese, G., Michel, E., Mazaud, A., Ther, O., Ikehara, M. and Itaki, T.: Impact of the Agulhas Return Current on the oceanography of the Kerguelen Plateau region, Southern Ocean, over the last 40 kyrs, Quat. Sci. Rev., 251, 106711, https://doi.org/10.1016/j.quascirev.2020.106711, 2021.

Cortese, G. and Abelmann, A.: Radiolarian-based paleotemperatures during the last 160 kyr at ODP Site 1089 (Southern Ocean, Atlantic Sector), Palaeogeogr. Palaeoclimatol. Palaeoecol., 182(3), 259–286, https://doi.org/10.1016/S0031-0182(01)00499-0, 2002.

Cortese, G. and Prebble, J.: A radiolarian-based modern analogue dataset for palaeoenvironmental reconstructions in the southwest Pacific, Mar. Micropaleontol., 118, 34–49, https://doi.org/10.1016/j.marmicro.2015.05.002, 2015.

Cortese, G., Abelmann, A. and Gersonde, R.: The last five glacial-interglacial transitions: A high-resolution 450,000-year record from the subantarctic Atlantic: ODP SITE 1089 SST RECORD OVER LAST 450 ka, Paleoceanography, 22(4), n/a-n/a, https://doi.org/10.1029/2007PA001457, 2007.

Crosta, X.: MD 218 / CROTALE cruise, RV Marion Dufresne. https://doi.org/10.17600/18000886, 2019.

Crosta, X., Pichon, J.-J. and Burckle, L. H.: Application of modern analog technique to marine Antarctic diatoms: Reconstruction of maximum sea-ice extent at the last glacial maximum, Paleoceanography, 13(3), 284–297, https://doi.org/10.1029/98PA00339, 1998.

Crosta, X., Sturm, A., Armand, L. and Pichon, J.-J.: Late Quaternary sea ice history in the Indian sector of the Southern Ocean as recorded by diatom assemblages, Mar. Micropaleontol., 50(3–4), 209–223, https://doi.org/10.1016/S0377-8398(03)00072-0, 2004.

Esper, O. and Gersonde, R.: New tools for the reconstruction of Pleistocene Antarctic sea ice, Palaeogeography, Palaeoclimatology, Palaeoecology, 399, 260–283, https://doi.org/10.1016/j.palaeo.2014.01.019, 2014.

Fatela, F. and Taborda, R.: Confidence limits of species proportions in microfossil assemblages, Marine Micropaleontology, 45(2), 169–174, https://doi.org/10.1016/S0377-8398(02)00021-X, 2002.

Ferry, A. J., Crosta, X., Quilty, P. G., Fink, D., Howard, W. and Armand, L. K.: First records of winter sea ice concentration in the southwest Pacific sector of the Southern Ocean, Paleoceanography, 30(11), 1525–1539, https://doi.org/10.1002/2014PA002764, 2015.

Fetterer, F., Knowles, K., Meier, W. N., Savoie, M. and Windnagel, A. K.: Sea Ice Index, Version 3, Boulder, Colorado USA. doi: https://doi.org/10.7265/N5K072F8, 2017.

Garcia, H., Weathers, K., Paver, C., Smolyar, I., Boyer, T., Locarnini, M., Zweng, M., Mishonov, A., Baranova, O. and Seidov, D.: World Ocean Atlas 2018. Vol. 4: Dissolved Inorganic Nutrients (phosphate, nitrate and nitrate+ nitrite, silicate), 2019a.

Garcia, H., Weathers, K., Paver, C., Smolyar, I., Boyer, T., Locarnini, M., Zweng, M., Mishonov, A., Baranova, O. and Seidov, D.: World Ocean Atlas 2018, Volume 3: Dissolved Oxygen, Apparent Oxygen Utilization, and Dissolved Oxygen Saturation., 2019b.

Gersonde, R. and Zielinski, U.: The reconstruction of late Quaternary Antarctic sea-ice distribution—the use of diatoms as a proxy for sea-ice, Palaeogeography, Palaeoclimatology, Palaeoecology, 162(3), 263–286, https://doi.org/10.1016/S0031-0182(00)00131-0, 2000.

Hernández-Almeida, I., Boltovskoy, D., Kruglikova, S. B. and Cortese, G.: A new radiolarian transfer function for the Pacific Ocean and application to fossil records: Assessing potential and limitations for the last glacial-interglacial cycle, Glob. Planet. Change, 190, 103186, https://doi.org/10.1016/j.gloplacha.2020.103186, 2020.

Lazarus, D.: A brief review of radiolarian research, Paläontol. Z., 79(1), 183–200, https://doi.org/10.1007/BF03021761, 2005.

Lazarus, D., Suzuki, N., Caulet, J.-P., Nigrini, C., Goll, I., Goll, R., Dolven, J. K., Diver, P. and Sanfilippo, A.: An evaluated list of Cenozic-Recent radiolarian species names (Polycystinea), based on those used in the DSDP, ODP and IODP deep-sea drilling programs, Zootaxa, 3999(3), 301, https://doi.org/10.11646/zootaxa.3999.3.1, 2015.

Leventer, A. and Science Party: Sabrina Coast: Marine Record of Cryosphere - Ocean Dynamics., 2014.

Locarnini, M., Mishonov, A., Baranova, O., Boyer, T., Zweng, M., Garcia, H., Seidov, D., Weathers, K., Paver, C. and Smolyar, I.: World ocean atlas 2018, volume 1: Temperature, 2018.

Lozano, J. A. and Hays, J. D.: Relationship of Radiolarian Assemblages to Sediment Types and Physical Oceanography in the Atlantic and Western Indian Ocean Sectors of the Antarctic Ocean, in Geological Society of America Memoirs, vol. 145, pp. 303–336, Geological Society of America, https://doi.org/10.1130/MEM145-p303, , 1976.

Lüer, V., Cortese, G., Neil, H. L., Hollis, C. J. and Willems, H.: Radiolarian-based sea surface temperatures and paleoceanographic changes during the Late Pleistocene–Holocene in the subantarctic southwest Pacific, Marine Micropaleontology, 70(3–4), 151–165, https://doi.org/10.1016/j.marmicro.2008.12.002, 2009.

Matsuzaki, K. M. and Itaki, T.: New northwest Pacific radiolarian data as a tool to estimate past sea surface and intermediate water temperatures: TEMPERATURE ESTIMATES AND RADIOLARIANS, Paleoceanography, 32(3), 218–245, https://doi.org/10.1002/2017PA003087, 2017.

Mazaud, A. and Michel, E.: MD 185 / Indien Sud-2 Cruise Report, RV Marion Dufresne. https://doi.org/10.17600/11200030, 2011.

Mazaud, A. and Michel, E.: MD 189 / Indien Sud-2 Cruise Report, RV Marion Dufresne. https://doi.org/10.17600/12200010, 2012.

https://doi.org/10.5194/essd-2021-148
Preprint. Discussion started: 30 June 2021

Moy, A. D., Howard, W. R., Bray, S. G. and Trull, T. W.: Reduced calcification in modern Southern Ocean planktonic foraminifera, Nat. Geosci., 2(4), 276–280, https://doi.org/10.1038/ngeo460, 2009.

McIlroy, D.: mapproj: Map Projections. https://CRAN.R-project.org/package=mapproj, 2020.

Nigrini, C. and Moore, T. C. J.: A guide to modern Radiolaria, Cushman Foundation for Foraminiferal Research, Washington, D.C., 1979.

Orsi, A. H., Whitworth, T. and Nowlin, W. D.: On the meridional extent and fronts of the Antarctic Circumpolar Current, Deep Sea Res. Part Oceanogr. Res. Pap., 42(5), 641–673, https://doi.org/10.1016/0967-0637(95)00021-W, 1995.

Panitz, S., Cortese, G., Neil, H. L. and Diekmann, B.: A radiolarian-based palaeoclimate history of Core Y9 (Northeast of Campbell Plateau, New Zealand) for the last 160 kyr, Mar. Micropaleontol., 116, 1–14, https://doi.org/10.1016/j.marmicro.2014.12.003, 2015.

Petrushevskaya, M. G.: Radiolarians of orders Spumellaria and Nassellaria of the Antarctic region, in Biological Reports of the Soviet Antarctic Expedition (1955 - 1958), edited by A. P. Andriyashev and P. V. Ushakov, pp. 2–186, 1967.

Petrushevskaya, M. G.: On the natural system of polycystine Radiolaria (Class Sarcodina), in Proceedings Second Planktonic Conference. Tecnoscienza, Rome, edited by A. Farinacci, pp. 981–992, 1971.

R Core Team: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/, 2020.

Radiolaria.org, http://www.radiolaria.org/, last access: 27 September 2019, n.d.

Rigual Hernández, A. S., Trull, T. W., Nodder, S. D., Flores, J. A., Bostock, H., Abrantes, F., Eriksen, R. S., Sierro, F. J., Davies, D. M., Ballegeer, A.-M., Fuertes, M. A. and Northcote, L. C.: Coccolithophore biodiversity controls carbonate export in the Southern Ocean, Biogeosciences, 17(1), 245–263, https://doi.org/10.5194/bg-17-245-2020, 2020.

Rogers, J. and De Deckker, P.: Radiolaria as a reflection of environmental conditions in the eastern and southern sectors of the Indian Ocean: A new statistical approach, Mar. Micropaleontol., 65(3), 137–162, https://doi.org/10.1016/j.marmicro.2007.07.001, 2007.

Rogers, J. and De Deckker, P.: Environmental reconstructions of the upper 500 m of the southern Indian Ocean over the last 40 ka using Radiolarian (Protista) proxies, Quaternary Science Reviews, 30, 876–886, https://doi.org/10.1016/j.quascirev.2011.01.006, 2011.

Schlitzer, R.: Ocean Data View. https://odv.awi.de, 2020.

Sumner, M.D.: orsifronts: Southern Ocean Frontal Distributions (Orsi), 2015

Suzuki, N. and Not, F.: Biology and Ecology of Radiolaria, in Marine Protists: Diversity and Dynamics, edited by S. Ohtsuka, T. Suzaki, T. Horiguchi, N. Suzuki, and F. Not, pp. 179–222, Springer Japan, Tokyo, https://doi.org/10.1007/978-4-431-55130-0_8, last access: 27 September 2019, 2015.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., Takahashi, K.,

https://doi.org/10.5194/essd-2021-148
Preprint. Discussion started: 30 June 2021

Vaughan, D., Wilke, C., Woo, K. and Yutani, H.: Welcome to the Tidyverse, Journal of Open Source Software, 4(43), 1686, https://doi.org/10.21105/joss.01686, 2019.

WOCE Data Products Committee: WOCE Data Products Committee, 2002, WOCE International Project Office, Southampton, UK., 2002.

WoRMS Editorial Board: WoRMS - World Register of Marine Species, http://www.marinespecies.org/ at VLIZ, last access: 27 September 2019, 2020.

Yasuhara, M., Huang, H.-H., Hull, P., Rillo, M., Condamine, F., Tittensor, D., Kučera, M., Costello, M., Finnegan, S., O'Dea, A., Hong, Y., Bonebrake, T., McKenzie, R., Doi, H., Wei, C.-L., Kubota, Y. and Saupe, E.: Time Machine Biology: Cross-Timescale Integration of Ecology, Evolution, and Oceanography, Oceanography, 33(2), https://doi.org/10.5670/oceanog.2020.225, 2020.

Zweng, M., Seidov, D., Boyer, T., Locarnini, M., Garcia, H., Mishonov, A., Baranova, O., Weathers, K., Paver, C. and Smolyar, I.: World ocean atlas 2018, volume 2: Salinity, 2019.