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RESEARCH ARTICLE

Tintinnid ciliates (marine microzooplankton) of the Ross Sea

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Abstract

For the Ross Sea, the only Marine Protected Area in Antarctica, available data on the tintinnid ciliates of the marine microzooplankton are mostly limited to nearshore waters near Terra Nova Bay or the vicinity of the McMurdo Sound. Here, we report results from a geographically extensive sampling across the Ross Sea conducted in December 2020. Material from plankton net tows (20 µm mesh), made at 38 stations spanning over 30° of latitude, was examined. We found 11 tintinnid species of varying commonality or rarity, many showing considerable morphological variability that is here documented. We found four forms that had not been previously reported from the Ross Sea. Based on our findings and previous reports, we assembled a species accumulation curve showing the growth in the inventory of tintinnid species recorded from the Ross Sea as a function of sampling effort and time since 1983. Extrapolation of the species accumulation curve, derived from sampling over the last 37 years, indicates that continued sampling will likely provide new species records, suggesting that the Ross Sea is under-sampled at present. This complicates efforts to detect temporal changes in species compositions, at least with regard to tintinnid ciliates. Comparing species accumulation curves for the Ross Sea and the relatively well-studied Weddell Sea, it appears that the Ross Sea may be more species-rich.

Keywords

Ross Sea Marine Protected Area; Antarctica, plankton, biodiversity

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To access the supplementary material, please visit the article landing page

Introduction

The Ross Sea is one of the very few relatively untouched marine ecosystems, having been subjected to little direct anthropogenic degradation or exploitation (Ainley 2010). It harbours a full complement of apex predators and has been identified as a key environment for conservation (Ballard et al. 2012). For these reasons and others, the Ross Sea Marine Protected Area was put into place in 2016, after many years of negotiations (e.g., Li & Yang 2018). Historically, studies of protists of the microzooplankton in Antarctic waters have focused on the waters of the Weddell Sea and Antarctic Peninsula (e.g., Garrison & Gowing 1993). While the Ross Sea is today perhaps one of the best studied of the Antarctic Seas with regard to the dynamics of phytoplankton, the microzooplankton have been relatively neglected (Smith et al. 2012; Smith et al. 2013).

Microzooplankton are a functional group. They are heterotrophic planktonic organisms of the plankton, classically defined as taxa ranging in size 20–200 µm and usually are dominated by ciliate and dinoflagellate taxa. They serve as the trophic link between small phytoplankton and higher trophic levels, typically copepods. The scarcity of basic data on microzooplankton, such as biomasses and activity rates, has been pointed out as problematic in modelling the food web of the Ross Sea (Pinkerton & Bradford-Grieve 2014). Detailed taxonomic data are sparse as well. A lack of data on dinoflagellate diversity has been acknowledged (Phan-Tan et al. 2018), and even the diversity of diatoms of the phytoplankton has, until recently, received little attention (Saggiomo et al. 2021). Here, the focus will be on the tintinnid ciliates of the microzooplankton of the Ross Sea. While generally a numerically minor component of the microzooplankton, the fact that each

species lives within a species-specific lorica or shell, identifiable using standard light microscopy, greatly facilitates study of diversity compared to other taxa of the microzooplankton (Dolan 2013). With this study, we seek to contribute to the baseline knowledge of the microzooplankton taxa of the Ross Sea.

It bears pointing out that tintinnid ciliates in the Antarctic Seas have been studied for over 100 years. The first publications were based on samples gathered during the German Südpolar Expedition of 1901–03 (Laackmann 1907, 1910). However, sampling has been highly irregular in time and space across most of the Antarctic Seas, and the Ross Sea is among the poorly sampled coastal seas of Antarctica (see figure 2 by Dolan et al. 2012). The first record of a tintinnid ciliate in the Ross Sea area appears to be the 1968 summary report by Littlepage, who stated that the microzooplankton community of McMurdo Sound was dominated by *Cymatocylis flava* (Littlepage 1968). The second record was about a decade later, the 1979 report by Azam et al. concerning organisms found under the Ross Sea Ice Shelf. They reported finding a tintinnid ciliate in a sample taken in 1977–78 from 200 m below the ice and described it as “compare *Salpincantha* sp.” (Azam et al. 1979: 453). About a decade later, Hopkins (1987) mentioned the three tintinnid species he found in the gut tracts of copepods and euphausiids in samples collected in 1983 from the McMurdo Sound. In subsequent years, several studies that focused on the ecology of microzooplankton were carried out near the US McMurdo Station or in McMurdo Sound; these identified the tintinnid taxa found to the genera level but not more specifically (i.e., Stoecker et al. 1995; Caron et al. 2000; Lonsdale et al. 2000; Dennett et al. 2001; Gowing et al. 2001; Rose et al. 2013). A singular exception was Rivkin & Putt, who reported on the filtration rates of *Cymatocylis vanhoeffeni* at unspecified “ambient temperatures”; they estimated clearance rates ranging up to $8 \mu\text{l cell}^{-1} \text{h}^{-1}$, a maximum clearance rate quite similar to those estimated for species in temperate waters (see table 4.2 by Montagnes 2013).

To our knowledge, the only complete species records of tintinnids (full binomials) in the literature concern relatively small regions of the Ross Sea. These are the several studies that provided complete binomial names for the tintinnid ciliates in waters near the Terra Nova Bay Station of Italy (Monti & Fonda Umani 1995; Fonda Umani et al. 1998; Monti & Fonda Umani 2000; Fonda Umani et al. 2002; Monti et al. 2016) and the nearshore waters between the Terra Nova Bay and the Ross Ice Shelf (Fonda Umani et al. 2005). In addition, Safi et al. (2012) reported the occurrence of tintinnid species in samples taken from deep-water sites between Cape

Adare and Scott Island. Thus, existing data, while substantial, are mostly limited to surveys of a relatively narrow band of the coastal zone bound roughly by 164°E and 173°E . Here, we report on the species found in samples gathered in December 2020 from an extensive set of stations across the Ross Sea, with the goal of providing a more complete inventory of the tintinnid species of the Ross Sea. Images of the forms encountered are provided, showing apparent morphological diversity of some common species. We also summarize records from the previous studies, and with the new data presented here, we provide a species catalogue for the Ross Sea. We present species accumulation curves as a function of sampling effort and time for the Ross Sea and compare it with data available for Weddell Sea, the well-studied Antarctic Sea.

Materials and methods

The data reported here are from samples gathered during the cruise of the Korean ice-breaker *Araon* in the Ross Sea in December 2020. The stations occupied covered a wide area of the Ross Sea and included stations in sea-ice zones and open waters (Fig. 1). Plankton net tows were performed at 38 stations to provide samples for the analysis of tintinnid species composition. A 20- μm pore size plankton net of 0.45 m diameter was towed from 100 m depth to the surface. Because the plankton net was not equipped with a flowmeter, the samples were not suitable for determining tintinnid cell concentrations. Net tow material was fixed using Lugol's (2% final concentration). Multiple aliquots of net tow material totalling 2–13 ml for each station (theoretically representing material from 55 to 600 L in the unlikely absence of net clogging) were examined in settling chambers using an Olympus IX71 inverted microscope equipped with differential interference contrast optics and a Canon Eos 5D Mark II digital camera. Tintinnids encountered were assigned species names based on lorica morphology, following Kofoid & Campbell (1929). Many ‘species’ so identified have long been suspected of being morphological variants of other more common species in Antarctic water (e.g., Sassi & Melo 1986; Boltovskoy et al. 1990; Williams et al. 1994) and are now known to be likely simply morphological variant of other species (e.g., Kim et al. 2013). Nonetheless, we employed Kofoid & Campbell's scheme to allow comparison with most of the previous studies (e.g., Monti & Fonda Umani 1995, 2000; Fonda Umani et al. 2002; Safi et al. 2012). Therefore, while we designate the forms encountered as species, the names actually represent the morphotypes depicted and described by Kofoid & Campbell (1929).

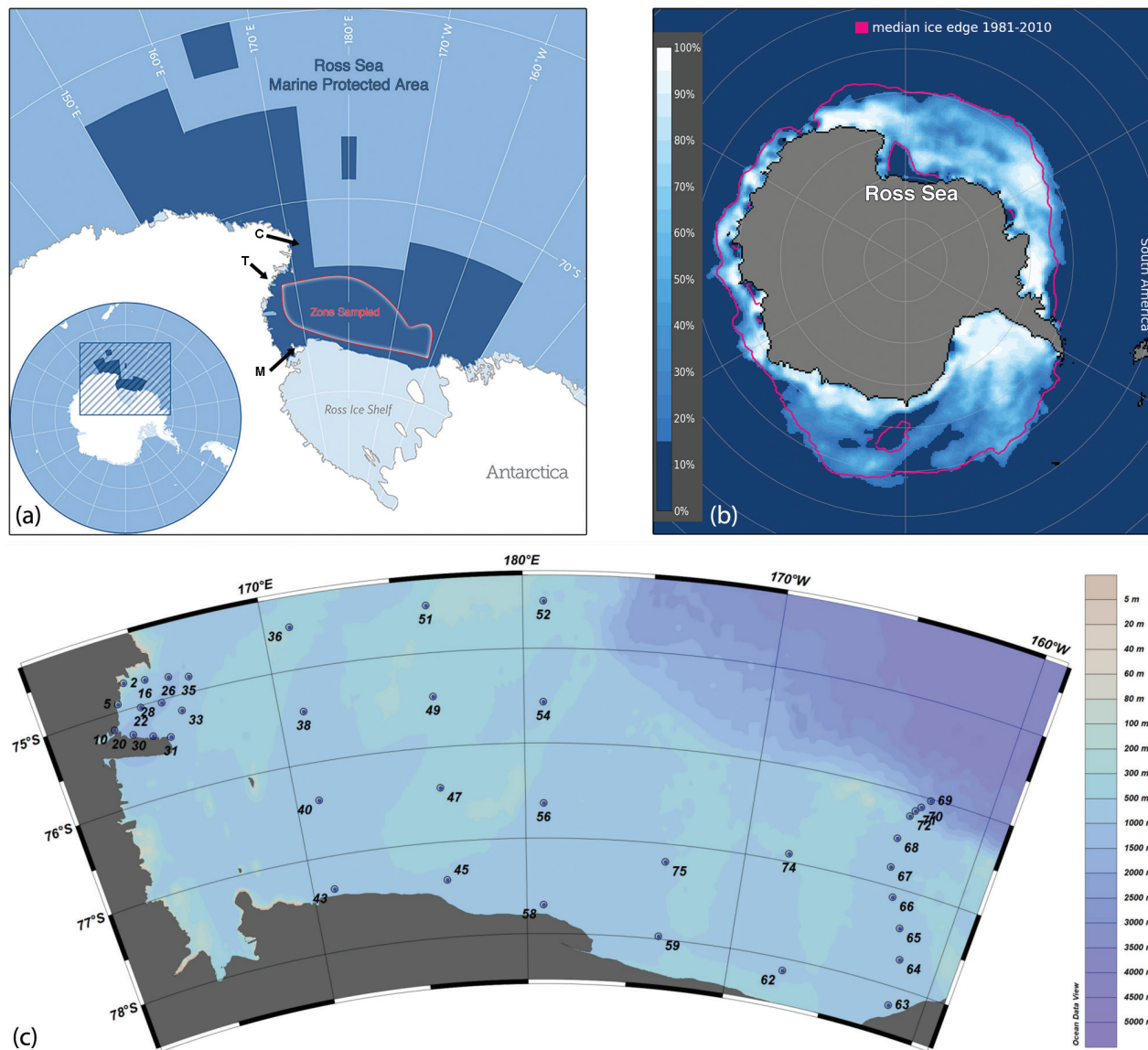


Fig. 1 (a) The area sampled relative to the Ross Sea Marine Protected Area, (b) sea-ice distributions in December 2020, when sampling was conducted and (c) locations of the 38 stations sampled for tintinnids. The area sampled covers a large part of the area traditionally considered as the Ross Sea, whereas the Marine Protected Area is much larger. In the map of the Ross Sea Protected Area (a), the letters C, T and M denote, respectively, Cape Adare, Terra Nova Bay and McMurdo Sound. In the map of sea-ice distributions (b), sea-ice conditions in December 2020 in the Ross Sea appeared to be typical for the month of December based on the long-term location of the median ice edge.

Only tintinnid loricas containing a ciliate cell were enumerated, in contrast to some of the previous studies (e.g., Monti et al. 2016; Monti-Birkenmeier et al. 2021). Empty loricas are unreliable evidence of living populations. Empty lorica can persist in the water column for long periods of time (Kato & Taniguchi 1993). Furthermore, persistence in the water column likely differs greatly among different taxa as sedimentation rates

of empty loricas vary by orders of magnitude among different taxa (Suzuki & Taniguchi 1995).

For each sample, we also noted the identity of the apparent dominant net phytoplankton group or groups (based on judgment of the surface area of the sedimentation chamber covered) as *Phaeocystis*, diatoms, dinoflagellates or some combination. Note that the apparent dominance of phytoplankton was judged from 20- μ m net

samples, in which small cells were likely poorly sampled. We included observations on the net phytoplankton as previous studies in the Ross Sea have reported that micro- and macrozooplankton assemblages can differ in terms of the identity of the dominant phytoplankton taxa (Stoecker et al. 1995; Dennett et al. 2001). Chlorophyll *a* concentrations were measured in discrete depth samples from several depths, usually in the upper 50 m of the water column, and analysed on board, as detailed by Dolan, Yang et al. (2013), and then integrated with depth to provide an estimate of surface layer concentration for each station.

To compare the Ross Sea tintinnid fauna to that of the Weddell Sea, tintinnid species records for the Ross Sea and the Weddell Sea were compiled using the previous database previously described by Dolan et al. (2012) and amended with any post-2012 records found using Google Scholar to locate articles containing both of the terms “Ross” and “tintinnid” or both of the terms “Weddell” and “tintinnid.” For each study found mentioning full binomials, the species found, the number of sites sampled and the year of sampling were noted.

Results

Tintinnid species encountered

We found a total of 11 species or morphotypes of tintinnids in the 38 samples. No single species was found at all stations. Only four species were found at a majority of the stations: *Laackmanniella naviculaefera*, *L. prolongata*, *Salpingella faurei* and *Cymatocyclus eucaudata*. The seven other species were found at a minority of stations (Fig. 2).

The loricas of the most commonly encountered species, *L. naviculaefera* and *L. prolongata*, had similar diameters (about 32 µm), but they differed in length. Length was variable in *L. prolongata* (200–310 µm), and the shorter loricas of *L. naviculaefera* (generally about 150 µm in length) were encrusted with diatom frustules, both empty and sometimes containing protoplasm. In our samples, the loricas of *L. prolongata* were free of diatoms. Also, the aboral end of the lorica in *L. naviculaefera* was irregular in outline compared to that of *L. prolongata* (Fig. 3).

The third and fourth most common species, *Salpingella faurei* and *Cymatocyclus eucaudata*, differed radically in size, representing, respectively, the smallest (12 µm diameter) and largest (75 µm diameter) forms found. Both species showed variable lorica morphologies. *Salpingella faurei* ranged in overall length from 65 µm to 165 µm (Fig. 4) and *C. eucaudata* ranged in overall length between 220 µm and 300 µm, with some specimens showed a posterior swelling of the aboral third of the lorica (Fig. 5).

Among the species we found at a minority of stations, the most common was the species with a more or less urn-shaped lorica, *Cymatocyclus convallaria/affinis*. It was found at about one-third of the stations. Specimens varied in the presence or absence of a suboral constriction of the lorica and swelling in width in the lower third of the lorica (Fig. 6). Thus, some specimens had loricas of a near conical shape.

Another large species, *Cymatocyclus drygalaskii*, was found in samples from six of the 38 stations. We assigned the name *C. drygalaskii* to specimens with loricas of an overall cylindrical shape, terminating with a distinct tail or horn (Fig. 7), distinguishing them from *C. eucaudata* (Fig. 5).

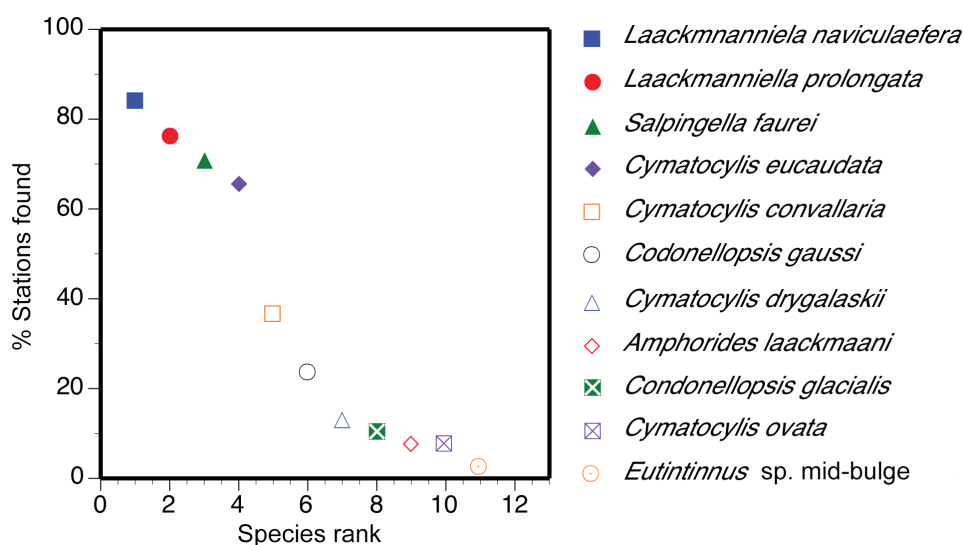


Fig. 2 Species rank occurrence for the 11 species or morphotypes found in the 38 stations sampled. No single species was found in all samples.

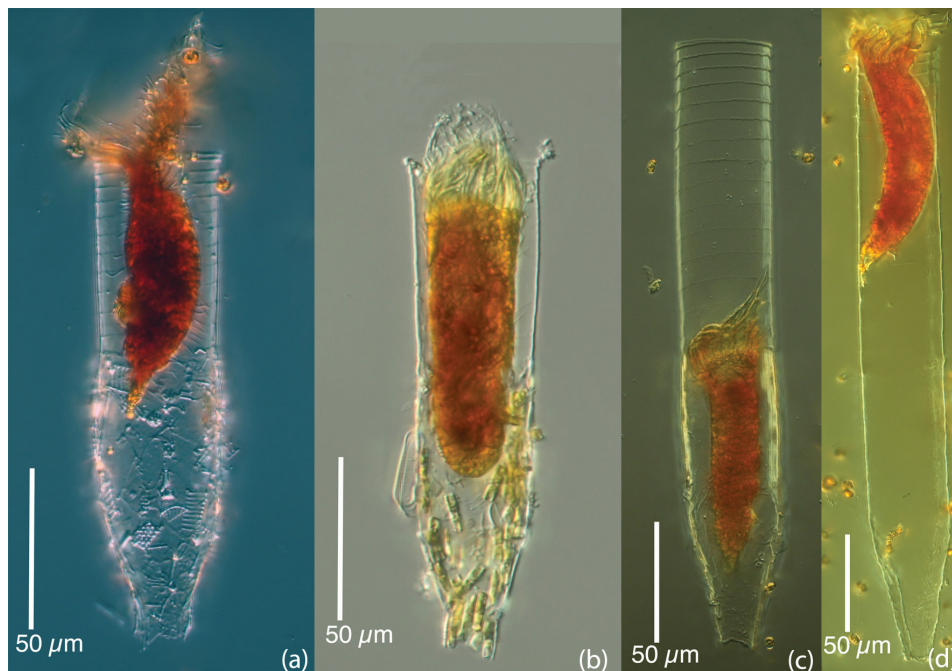


Fig. 3 The most commonly encountered tintinnid species (a–b) *Laackmanniella naviculaefera* and (c–d) *L. prolongata*. Note the difference in scale bars. *Laackmanniella naviculaefera* always had diatom frustules encrusted on the lorica, (b) occasionally frustules contained cytoplasm. The loricas of *L. prolongata* were without diatom frustules. The specimens were from stations (a) 38, (b) 16, (c) 58 and (d) 40.

The species was found in low abundances compared to *C. eucaudata* found in the same samples (see the Supplementary material). The *C. drygalaskii* specimens varied considerably with regard to the length of the aboral tail or horn.

We encountered forms of *Codonellopsis* of two more or less distinct lorica shapes (Fig. 8). We attributed the name *C. gaussi* to specimens whose loricas showed a pronounced bulge in the posterior third of the lorica, ending in a fine point, with or without a short aboral tail or horn. The form was the fifth most common species found. We attributed the name *C. glacialis* to specimens without a pronounced bulge in the posterior third of the lorica and with a pointed aboral end lacking a tail or horn. This latter form was found much less frequently than *C. gaussi* (Fig. 2) and was found in samples both with and without *C. glacialis* (see the Supplementary material). There was considerable variability in lorica morphologies among specimens we considered as two distinct species. For example, *C. glacialis* lorica shapes varied from a near conical aboral end to ones with a posterior bulge, and *C. gaussi* specimens varied with regard to lorica length as well having a tail or horn at the aboral end of the lorica.

We encountered three species (Fig. 9) that could be termed rare as they were found in the samples from either only three or a single station. These were

Amphorides laackmanni and *Cymatocylis ovata*, found in material from three stations, and an apparently undescribed *Eutintinnus* species, found at a single station. The lorica of this new species measured 140 µm in length, with a lorica oral opening diameter of 30 µm; it showed a pronounced bulge in the middle of the lorica about 55 µm across and an aboral lorica opening diameter of 25 µm. Only two specimens were found, but they were nearly identical. All three of the rare taxa are new species records for the Ross Sea.

Station-by-station results

A summary of our results, station by station, is given in Table 1. For complete species records for each station and temperature, salinity and other data for the top 100 m of each station, see the Supplementary material. A very wide range of phytoplankton compositions and chlorophyll *a* concentrations (0.04–4.98 µg l⁻¹) was encountered among the stations sampled. In contrast, among the stations, there was little relative variability of near surface temperature (°C avg. ± sd -1.04 ± 0.44) or salinity (ppt avg. ± sd 34.3 ± 0.35). The identity of the dominant tintinnid species and the number of species found (2–10 species) also varied widely. However, casual inspection suffices to show that neither the identity of the dominant

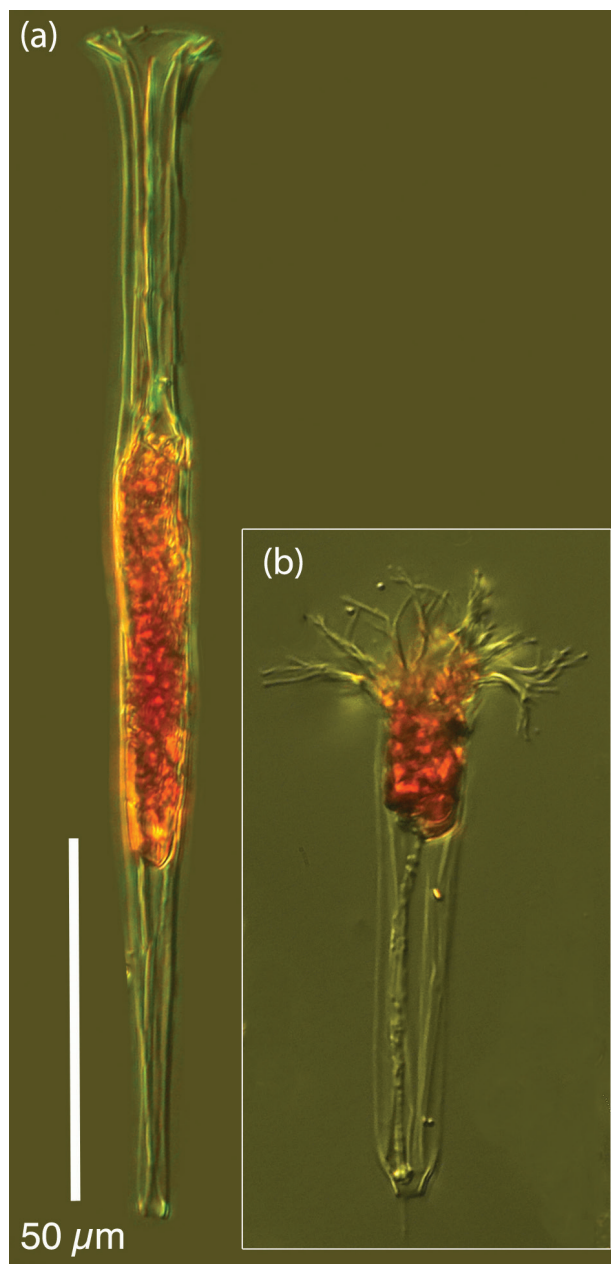


Fig. 4 The third most commonly encountered tintinnid species, *Salpingella faurei*. Specimens shown are from stations (a) 36 and (b) 58. The long form was more common than the short form, and many specimens of intermediate lengths were encountered.

tintinnid species nor the number of tintinnid species found was related to phytoplankton composition (as identity of dominant group), chlorophyll *a* concentration, water column depth, surface water temperature and salinity or other conditions. For example, at station 54, the highest number of tintinnid species was found (10), and it was dominated by one of the largest tintinnids

encountered, *Cymatocylis eucaudata*; the phytoplankton community was dominated by *Phaeocystis* and diatoms with a chlorophyll *a* concentration of $2.46 \mu\text{g l}^{-1}$. A nearly identical phytoplankton community was encountered in terms of dominant taxa and chlorophyll *a* concentrations at stations 71 and 72, but with a species-poor tintinnid community (three species), dominated by the smallest tintinnid species encountered, *Salpingella faurie*.

The stations located near one another often had the same number of tintinnid species and the same dominant species. However, the geographic location of the stations (i.e., sea-ice zone, open water, east versus west and distance from shore) appeared unrelated to the species richness of the tintinnid assemblage recorded (Fig. 10). Overall, we found no simple associations with species richness. It should be noted, though, that each sample represented a single ‘snapshot,’ we have no information on conditions preceding the sampling and those conditions likely determined the composition of the tintinnid community found on the day of sampling.

Discussion

In our samples, obtained from stations across the Ross Sea, we found 11 tintinnid species, among which four had not previously been reported from the Ross Sea. A summary of all the records of the tintinnid species now known from the Ross Sea is given in Table 2. We found several species that had been previously reported from the Ross Sea, most of which had been found multiple times. These were the species *Condellopsis gaussi*, *Condonellopsis glacialis*, *Cymatocylis convallaria*, *Cymatocylis drygalaski*, *Laackmanniella naviculaefera* and *Laackmanniella prolongata*. However, with the exception of the *Laackmanniella* spp., the previously reported species we found were not commonly encountered in our samples (Fig. 2). Furthermore, one of the species we found most often in our samples, *Salpingella faurei*, had not previously been found in the Ross Sea. We did not encounter 11 tintinnid species previously reported from the Ross Sea. The disparity between our species list and previous studies is likely due to, at least in part, the fact that our sampling was largely offshore, while previous sampling was largely nearshore. It should be noted, though, that our samples represented material from large volumes of water relative to previous studies. Also, of the forms we found that appear to be new records, three of the four are small species with transparent hyaline lorica (Figs. 4, 9a, b), perhaps easily overlooked when examining samples.

A complicating factor in compiling species records is the fact that most reports do not include illustrations of

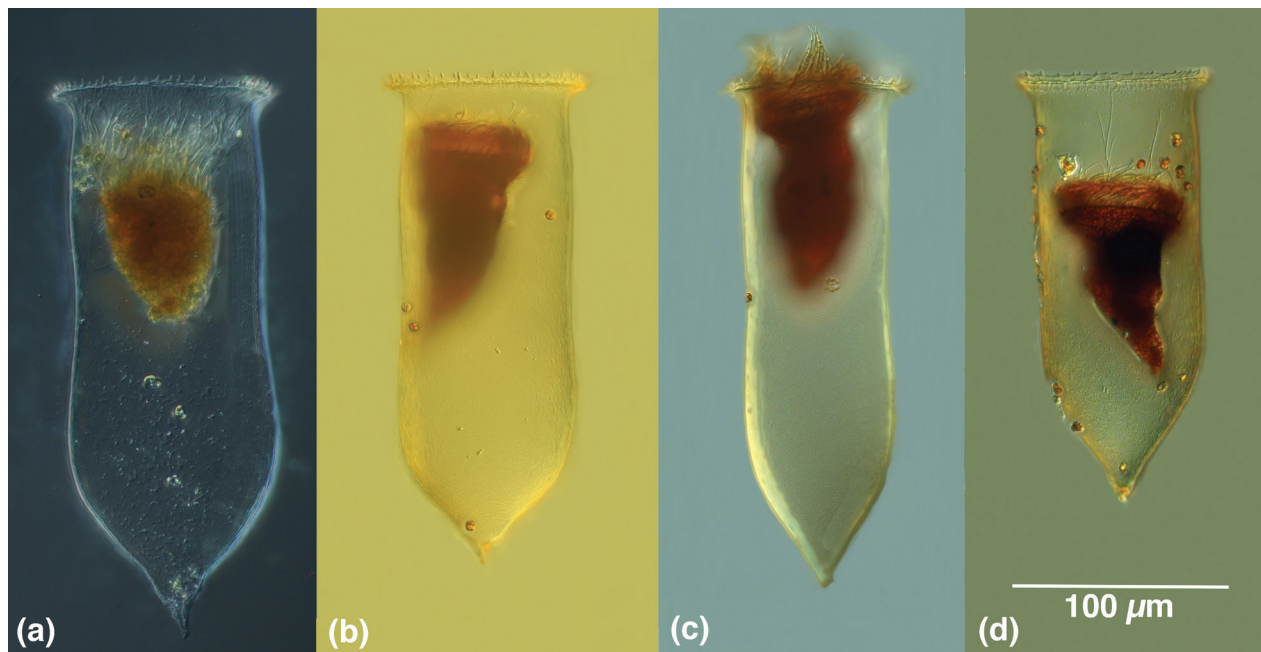


Fig. 5 Morphological variability among specimens of *Cymatocyclus eucaudata*, the fourth most commonly encountered species. We assigned the name *C. eucaudata* to all specimens with loricas of an overall cylindrical shape and with a pointed aboral end, lacking an aboral horn or tail (compare to *C. drygalskii* below). Note that the specimens varied in total length from about 200 µm to 260 µm, and some showed a more or less distinct swelling of the posterior third of the lorica. The specimens shown were from stations (a) 33, (b) 45, (c) 4 and (d) 49.

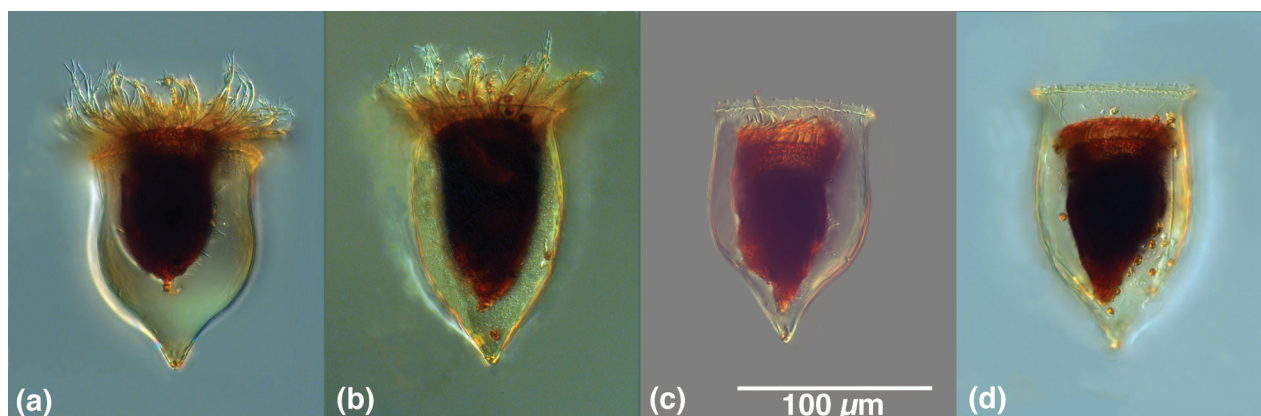


Fig. 6 Examples of specimens of *Cymatocyclus convallaria/affinis* encountered, showing variability of the overall shape, from urn-shaped to nearly conical loricas. The specimens shown are from stations (a) 58, (b) 36, (c) 49 and (d) 62.

the forms to which precise names have been attributed. It is possible that a single morphotype is identified as belonging to different species in different reports. Contrarily, some authors may group various morphotypes under a single species name that are reported as distinct species by another author. Unfortunately, at this time, there is little clarity with regard to species boundaries among tintinnids, genetic or morphological (e.g., Santoferrara & McManus 2021; Santoferrara

et al. 2017). We reported here the forms corresponding to the different morphotypes illustrated and described in the classic tintinnid ciliate monograph (Kofoid & Campbell 1929) as “species.” The distinct morphotypes may or may not correspond with genetically distinct forms and also may or may not correspond with different environmental conditions. Prudence dictates distinguishing the different morphotypes as distinct species found while providing data on which forms

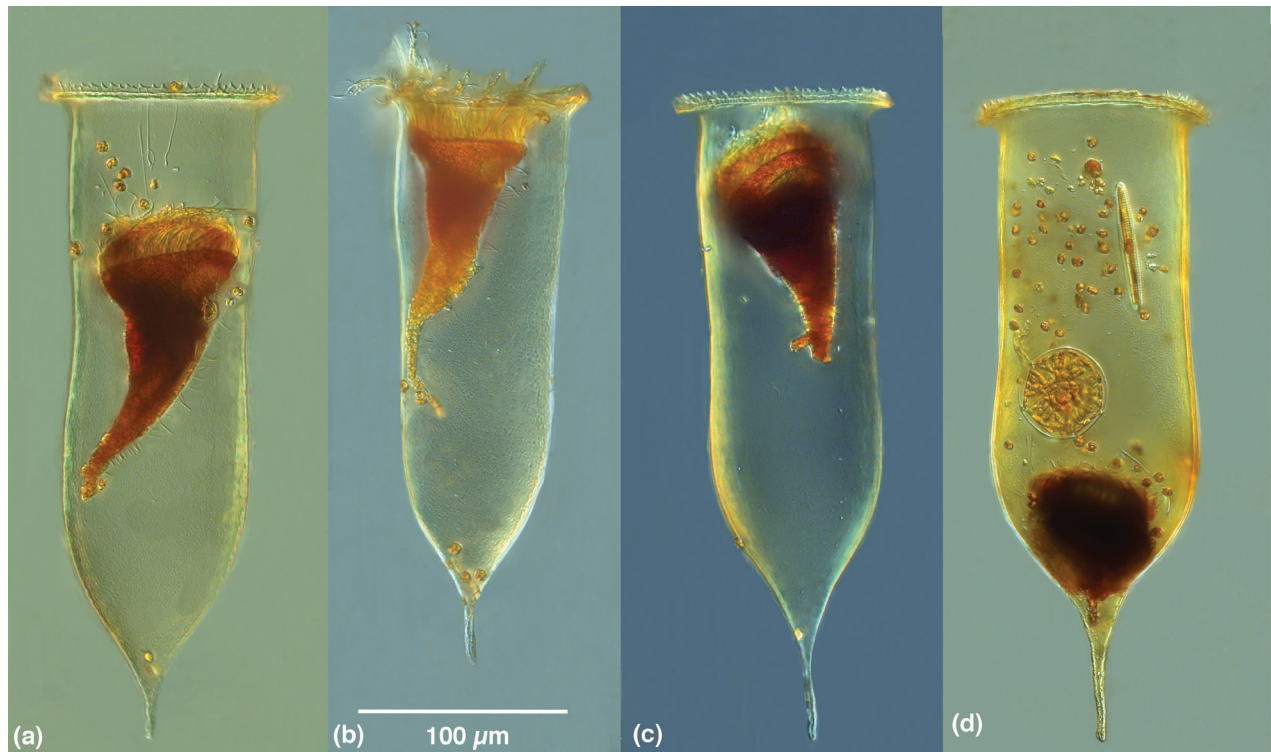


Fig. 7 Examples of specimens of *Cymatocylis drygalaskii*. The tail or horn of the aboral end of the lorica varied in absolute lengths and in lengths relative to the overall length of the loricas. The specimens shown were found in the samples from stations (a) 54, (b) 49, (c) 54 and (d) 59.

were attributed which names (Figs. 3–9) and which forms were found where and when (Supplementary material).

The major goal of our study was to provide an improved baseline catalogue of tintinnid species for the Ross Sea as previous sampling had been confined to near-shore waters. Based on our sampling and previous reports, the tintinnid fauna of the Ross Sea consists of 22 species or morphotypes. The number is similar to the number of species reported from the historically well-studied Weddell Sea of 21 species. Interestingly, the combining the species lists for the two seas yields a list of 34 species, with only nine species common to both lists (Table 3). For both seas, species occurrences are largely from studies employing examination of whole water samples. However, both have also been sampled using plankton nets (this study for the Ross Sea and Balech & El-Sayed [1965] for the Weddell Sea). Both seas have been sampled almost exclusively during the austral summer. One plausible explanation for the differences in the two inventories tintinnid species is that the two seas differ in one or more characteristics resulting in distinct tintinnid faunas. In this regard, it is of interest to compare the species pools of the two systems in terms of the lorica

oral diameter as this feature can characterize tintinnid faunas (e.g., Dolan, Landry et al. 2013). Notably, the species lists of both seas are clearly dominated by species of *Cymatocylis*, all of which have very similar lorica oral diameters.

An alternative explanation for the disparity in the species catalogues for the Ross Sea and the Weddell Sea is under-sampling. This is to say, sampling thus far has been insufficient, with only a fraction of all of the resident tintinnid species found. If this is so, the apparent difference in the species lists of the two seas represents only sampling error. To evaluate this possibility, we plotted species discovery for both seas as a function of the number of sites sampled and time (Fig. 11). Under-sampled systems should show increases in the species inventory with sampling. We found that the Ross Sea species list is likely to grow with continued sampling. In contrast, the Weddell Sea may be fully sampled as marked increases in the total number of sites sampled since the 1980s have not resulted in any increase in the species inventory. We conclude then that the Ross Sea likely harbours more tintinnid species than known at present. A high species diversity may be related to the more pristine condition of the Ross Sea compared to the Weddell Sea. As noted above, the Ross

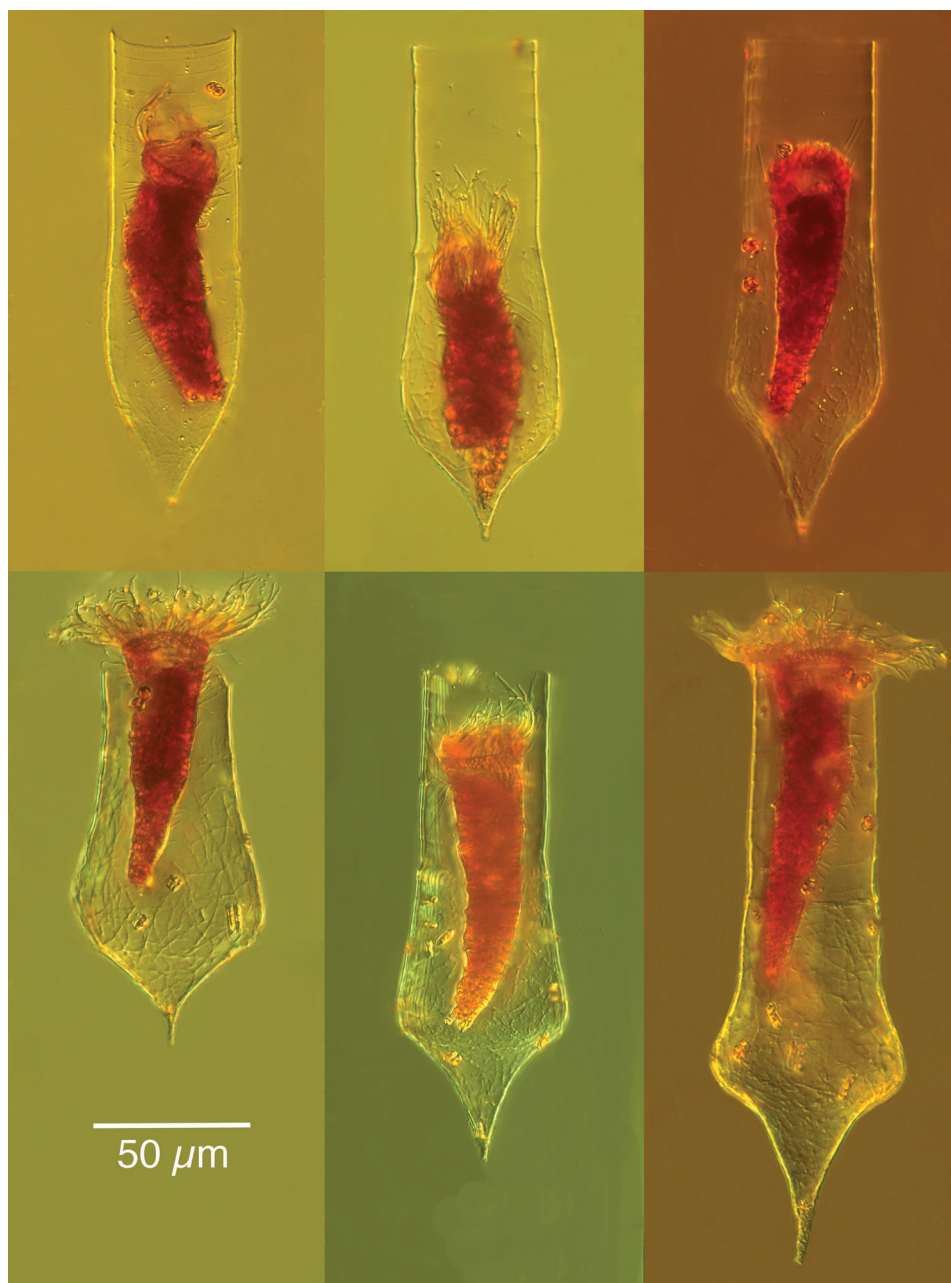


Fig. 8 Specimens of *Codonellopsis gausi* (top row) and *C. glacialis* (bottom row). The loricas of *C. gausi* specimens varied with regard to overall length and posterior tail or horn. The loricas of *C. glacialis* specimens varied with regard to the swelling in the posterior third. The *C. gausi* specimens shown were found in samples from stations (a) 56, (b) 38 and (c) 36. The *C. glacialis* specimens were found in samples from stations (d) 49, (e) 43 and (f) 47.

Sea is among the very few untouched marine systems (Ainley 2010), justifying in large part of the creation of the Ross Sea Marine Protected Area (Li & Yang 2018). However, regardless of the reasons for an apparently high diversity, the plots of sampling effort and species discovery indicate that diagnosing changes in the tintinnid

assembly of the Ross Sea should likely not rely on the detection of new species as the system is under-sampled. Regardless of any environmental change, new species will likely be found with continued sampling in the Ross Sea. Any shifts in ecosystem may be more readily reflected in changes in the identity of the few dominant forms.

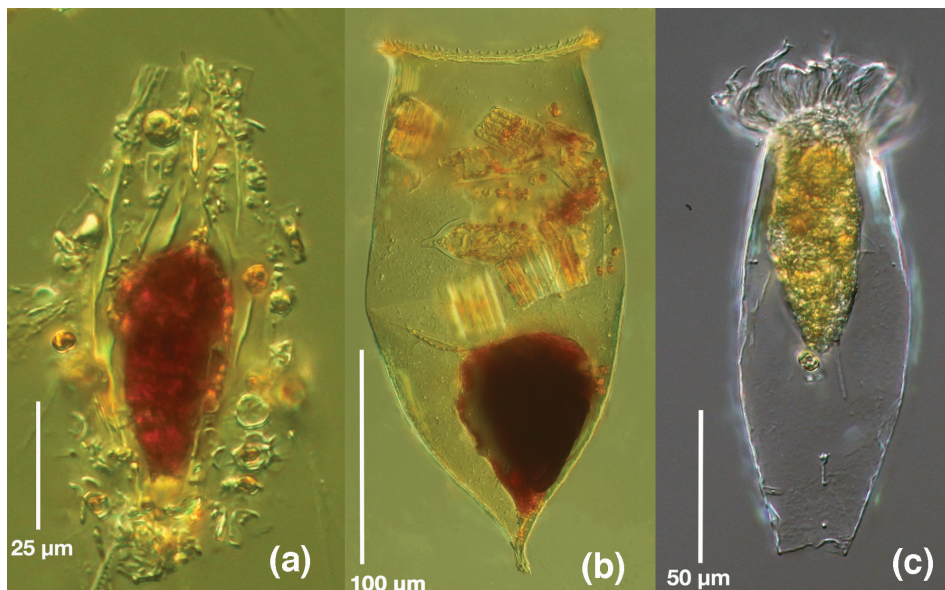


Fig. 9 The three most rarely species encountered: (a) *Amphorides laackmanni* (specimen from station 56), (b) *Cymatocylix ovata* (specimen from station 56) and (c) an apparently undescribed species of *Eutintinnus*. Two nearly identical specimens of the *Eutintinnus* species were found in the sample from station 54.

Table 1 Summary data. The chlorophyll *a* concentrations varied over two orders of magnitude among stations.

Station	Date ^a	Lat. (°N)	Long. (°W)	Z max ^b	Chl (µg l ⁻¹) ^{c,d}	Chl z ^{d,e}	Dom phyto ^f	No. of spp. ^g	Dominant tintinnid sp. ^h
2	6	-74.72	164.28	457	nd	nd	P&D	3	<i>L. prolongata</i>
5	7	-74.92	163.82	502	0.47	35	P&D	4	<i>L. prolongata</i>
10	7	-75.17	163.40	745	0.96	60	D	2	<i>L. prolongata</i>
16	8	-74.75	165.11	692	0.79	65	P&D	2	<i>L. prolongata</i>
20	8	-75.28	164.06	1222	0.23	100	P&D	2	<i>L. prolongata</i>
22	9	-75.02	164.66	879	0.90	40	D	3	<i>L. prolongata</i>
26	9	-74.79	166.02	882	0.76	50	D	2	<i>L. prolongata</i>
28	10	-75.03	165.52	1120	0.59	70	D	4	<i>L. prolongata</i>
30	10	-75.35	164.82	670	0.20	30	D	3	<i>L. prolongata</i>
31	10	-75.41	165.50	816	0.17	20	D	2	<i>L. naviculaefera</i>
33	10	-75.17	166.22	802	1.23	32	P&D	3	<i>L. prolongata</i>
35	11	-74.84	166.80	792	0.45	60	D	4	<i>L. prolongata</i>
36	11	-74.55	171.00	349	nd	nd	P	6	<i>L. naviculaefera</i>
38	11	-75.45	171.00	561	nd	nd	P	4	<i>S. faurie</i>
40	111	-76.40	171.00	620	3.25	15	P	4	<i>L. prolongata</i>
43	12	-77.35	171.00	857	2.37	15	P	4	<i>C. eucaudata</i>
45	12	-77.40	176.30	618	3.49	30	P	3	<i>S. faurie</i>
47	13	-76.43	176.30	406	3.57	15	P&D	7	<i>L. prolongata</i>
49	13	-75.47	176.30	359	1.53	25	P	7	<i>L. prolongata</i>
51	14	-74.50	176.30	301	0.04	30	D	6	<i>C. convallaria/aff</i>
52	14	-74.50	-179.20	293	0.15	33	D	4	<i>L. naviculaefera</i>
54	14	-75.57	-179.20	563	2.46	25	P&D	10	<i>C. eucaudata</i>
56	15	-76.63	-179.20	627	1.86	11	P&D	6	<i>S. faurie</i>
58	15	-77.70	-179.20	652	1.02	16	P	4	<i>C. eucaudata</i>
59	16	-77.97	-173.56	529	4.22	20	P&D	4	<i>L. prolongata</i>
62	16	-78.13	-167.26	561	1.96	50	D	6	<i>L. naviculaefera</i>
63	17	-78.20	-161.72	603	4.98	70	Din&D	2	<i>L. naviculaefera</i>
64	17	-77.71	-161.85	677	4.30	30	Din&D	5	<i>L. naviculaefera</i>

(Continued)

Table 1 (Continued) Summary data.

Station	Date ^a	Lat. (°N)	Long. (°W)	Z max ^b	Chl ($\mu\text{g l}^{-1}$) ^{c,d}	Chl z ^{d,e}	Dom phyto ^f	No. of spp. ^g	Dominant tintinnid sp. ^h
65	17	-77.40	-162.29	645	3.36	40	Din&D	7	<i>C. convallaria</i> /aff
66	18	-77.11	-163.01	616	3.56	42	Din&D	4	<i>C. convallaria</i> /aff
67	18	-76.81	-163.46	575	1.51	30	D	3	<i>L. naviculaefera</i>
68	18	-76.50	-163.53	562	2.25	30	P&D	3	<i>L. naviculaefera</i>
69	18	-76.02	-162.58	2274	0.97	32	D	2	<i>S. faurie</i>
70	19	-76.11	-162.90	1620	0.97	40	P&D	2	<i>S. faurie</i>
71	19	-76.17	-163.10	990	2.43	30	P&D	3	<i>S. faurie</i>
72	19	-76.23	-163.27	459	2.59	21	P&D	3	<i>S. faurie</i>
74	20	-76.92	-168.06	458	0.27	18	D	2	<i>S. faurie</i>
75	20	-77.19	-173.57	517	0.17	40	D	3	<i>S. faurie</i>

^aDate in December 2020. ^bTotal depth of station. ^cChlorophyll *a* concentrations. ^dThe absence of data is indicated as nd. ^eAverage integrated values from the surface to the depth (m). ^fThe dominant net phytoplankton taxa: *Phaeocystis* (P), diatoms (D), D dinoflagellates (Din) or combinations. ^gThe number of tintinnid species found. ^hThe numerically dominant tintinnid species, genera abbreviated as follows *Laackmaniella* (L.), *Salpingella* (S.) and *Cymatocylis* (C.).

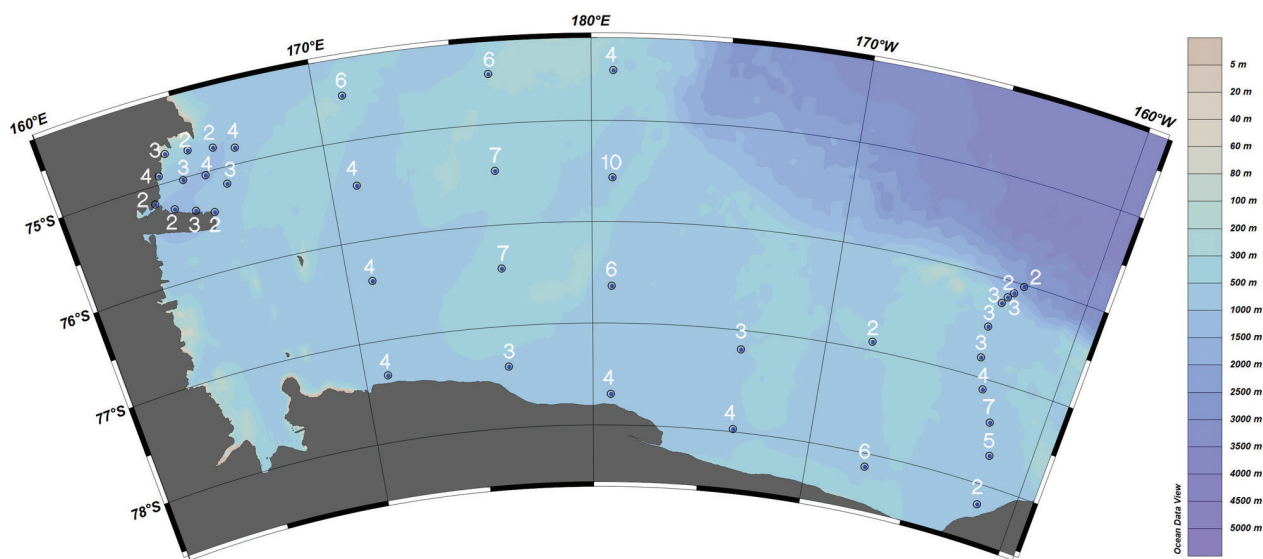


Fig. 10 The number of tintinnid species found at each location sampled. Species richness appeared largely unrelated to station location at least with regard to east versus west, distance from shore and total water column depth. Station locations relative to sea-ice concentrations are shown in Fig. 1, and exact locations are given in Table 2.

As a final note, it is only from work in the Ross Sea that we have some data on feeding and growth rates of Antarctic tintinnids. To our knowledge, the only data on filtration rates of tintinnid ciliates in Antarctic waters are those reported by Rivkin & Putt (1987), who reported maximum rates of $10 \mu\text{l h}^{-1} \text{ cell}^{-1}$, similar to those estimated for temperate sea species. Likewise, the only growth rates known for Antarctic tintinnids are those reported by Lonsdale et al. (2000) from the control treatments of their copepod predation experiments. They reported growth rates of mixed assemblages of tintinnid species of 1.0 d^{-1} equivalent to generation times of about

16 hours, again, similar to maximum growth rates estimated for tintinnid species in temperate waters (i.e., table 4.3 by Montagnes 2013). Such maximum physiological rates at ambient temperatures support the view that tintinnids in the Ross Sea are likely to be ecologically relevant.

Conclusion

Based on the data reported here and in past studies, the tintinnid fauna of the Ross Sea is rich, consisting of 22 species or morphotypes. However, based on data from any

Table 2 List of the 22 tintinnid species of the Ross Sea reported as full binomials and/or with illustrations, with the year first found, and years subsequently found, if any. The 11 species names in boldface are those found in our samples, and those with asterisks are our new species records for the Ross Sea.

Species name	First reference (year)	Source ^a	Years subsequently found ^b
Amphoroides laackmanni*	2020	TS	Not applicable
Condellopsis gaussi	1983	2	1988, 1989, 1990, 1995, 1997, 2008, 2011, 2020
Condonellopsis glacialis	1988	3	1989, 1990, 1995, 1998, 2011, 2020
<i>Coxiella frigida</i>	1988	3	2011
<i>Cymatocylis conica</i>	1988	3	None
Cymatocylis convallaria	1995	4	2008, 2011, 2020
<i>Cymatocylis cristallina</i>	2011	5	None
Cymatocylis drygalaski	1988	3	1989, 1990, 1995, 1997, 2008, 2011, 2020
Cymatocylis eucaudata	1990	3	2020
<i>Cymatocylis flava</i>	1968	1	1988
<i>Cymatocylis folliculus</i>	1990	3	None
<i>Cymatocylis glans</i>	1990	3	None
<i>Cymatocylis nobilis</i>	1990	3	None
Cymatocylis ovata*	2020	TS	Not applicable
<i>Cymatocylis subconica</i>	1990	3	None
<i>Cymatocylis vanhoffeni</i>	1983	2	1985, 1988, 1989, 1995, 1997, 2008, 2011
Eutintinnus new sp.*	2020	TS	Not applicable
Laackmanniella naviculaefera	1983	2	1987, 1988, 1990, 1995, 1997, 2008, 2011, 2020
Laackmanniella prolongata	1987	3	1988, 1990, 1997, 2020
<i>Salpingella costata</i>	2011	5	None
<i>Salpingella decurtata</i>	2011	5	None
Salpingella faurie*	2020	TS	Not applicable

^aLittlepage 1968 (1); Hopkins 1987 (2); Monti & Fonda Umani 1995 (3); Monti & Fonda Umani 2000 (4); Monti et al. 2016 (5). ^bRivkin & Putt 1987 (1985); Monti & Fonda Umani 1995 (1988); Monti & Fonda Umani 1995 (1989); Monti & Fonda Umani 1995 (1990); Monti & Fonda Umani 2000 (1995); Fonda Umani et al. 2002 (1997); Safi et al. 2012 (2008); Monti et al. 2016 (2011); this study (TS; 2020).

Table 3 The tintinnid species of the Ross Sea and the Weddell Sea reported as full binomials with the year first found and reference for the first Weddell Sea report of first occurrence. The 11 species names in boldface are those found in our samples, and those with asterisks are our new species records for the Ross Sea.

Species name	Ross Sea ^a	Weddell Sea ^a	Weddell Sea reference ^a
<i>Amphorellopsis quinquealata</i>	∅	1983	Heinbokel & Coats 1986
<i>Amphoroides laackmanni</i>	2020	∅	∅
<i>Codonellopsis balechi</i>	∅	1985	Barria de Cao 1987
<i>Codonellopsis frigida</i>	∅	1963	Balech & El-Sayed 1965
Condellopsis gaussi	1983	1963	Balech & El-Sayed 1965
Condonellopsis glacialis	1988	1983	Heinbokel & Coats 1986
<i>Coxiella frigida</i>	1988	∅	∅
<i>Cymatocylis brevicaudata</i>	∅	1983	Heinbokel & Coats 1986
<i>Cymatocylis crassa</i>	∅	1983	Heinbokel & Coats 1986
<i>Cymatocylis culcullus</i>	∅	1983	Heinbokel & Coats 1986
<i>Cymatocylis cylindroides</i>	∅	1983	Heinbokel & Coats 1986
<i>Cymatocylis conica</i>	1988	∅	∅
Cymatocylis convallaria	1995	1963	Balech & El-Sayed 1965
<i>Cymatocylis cristallina</i>	2011	∅	∅
Cymatocylis drygalaski	1988	1963	Balech & El-Sayed 1965
<i>Cymatocylis eucaudata</i>	1990	∅	∅
Cymatocylis flava	1988	1968	Littlepage 1968
<i>Cymatocylis folliculus</i>	1990	∅	∅
<i>Cymatocylis glans</i>	1990	∅	∅
<i>Cymatocylis nobilis</i>	1990	∅	∅
<i>Cymatocylis ovata</i>	2020	∅	∅
<i>Cymatocylis parva</i>	∅	1983	Heinbokel & Coats 1986

(Continued)

Table 3 (Continued) The tintinnid species of the Ross Sea and the Weddell Sea reported as full binomials with the year first found and reference for the first Weddell Sea report of first occurrence.

Species name	Ross Sea ^a	Weddell Sea ^a	Weddell Sea reference ^a
<i>Cymatocylis scyphus</i>	∅	1983	Heinbokel & Coats 1986
<i>Cymatocylis subconica</i>	1990	∅	∅
<i>Cymatocylis subrotundata</i>	∅	1985	Barria de Cao 1987
<i>Cymatocylis typica</i>	∅	1983	Heinbokel & Coats 1986
<i>Cymatocylis vanhoeffeni</i>	1983	1963	Balech & El-Sayed 1965
<i>Eutintinnus new sp</i>	2020	∅	∅
<i>Laackmanniella naviculaefera</i>	1983	1963	Balech & El-Sayed 1965
<i>Laackmanniella prolongata</i>	1987	1983	Heinbokel & Coats 1986
<i>Salpingella costata</i>	2011	∅	∅
<i>Salpingella decurtate</i>	2011	∅	∅
<i>Salpingella faurie</i>	2020	1985	Barria de Cao 1987
<i>Salpingella laackmanni</i>	∅	1963	Balech & El-Sayed 1965

^a∅ indicates no record.

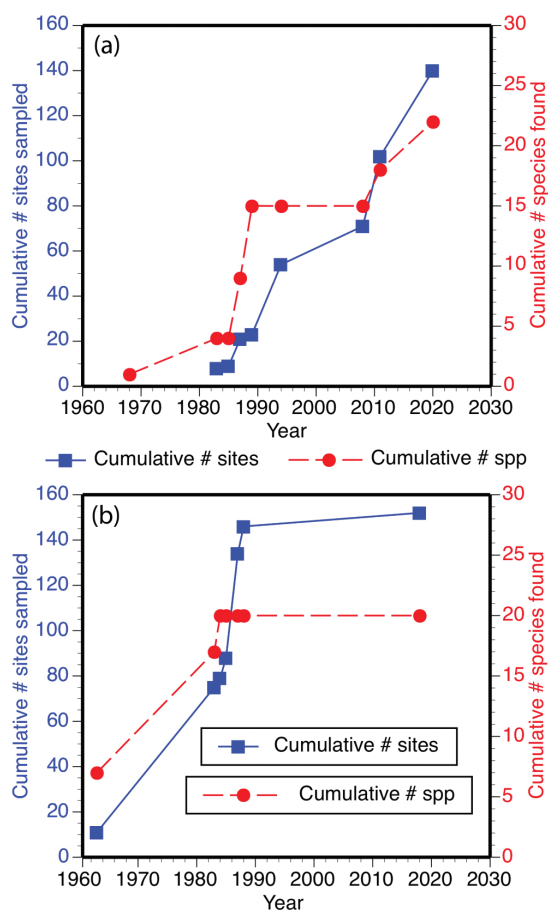


Fig. 11 Plots of the cumulative number of species recorded as a function of the number of sites sampled and year for the Ross Sea and the Weddell Sea. Data for the Ross Sea plots are from the references given in Table 2. Data for the Weddell Sea are from Balech & El-Sayed (1965); Barria de Cao (1987); Heinbokel & Coats (1986); Boltovskoy et al. (1989); Alder (1995). Extrapolation of the Ross Sea plots suggests an increase in the species inventory with continued sampling, in contrast to the Weddell Sea plots.

given study, the composition of tintinnid assemblages varies considerably, suggesting high temporal and spatial variability and/or under-sampling. We encountered previously unreported species, and the overall species inventory appears to be growing with sampling effort. Consequently, it is likely that continued sampling will reveal the presence of more previously unreported species in the Ross Sea.

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Disclosure statement

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Note

While in press, a new paper (Wang et al. 2022), including data on Ross Sea tintinnids, appeared. Data from 13 stations sampled in January 2020 are reported. No new tintinnid species records for the Ross Sea were documented. Six species, previously noted, were found (with occupied lorica): *Condonellopsis gaussi*, *Condonellopsis glacialis*, *Cymatocyliis convallaria*, *Cymatocyliis cristallina*, *Cymatocyliis drygalskii*, *Cymatocyliis vanhoeffeni* and *Laackmanniella prolougata*. Inclusion of the new data would only slightly alter Fig. 11. The cumulative number of Ross Sea sites sampled would increase from 140 to 153 sites.