

Survival of tropical ballast water organisms during a cruise from the Indian Ocean to the North Sea

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Abstract. In an assessment of non-indigenous species transported by international ship traffic to German waters, commissioned by the German Federal Environmental Agency, the survival of tropical plankton organisms in ballast water was studied by accompanying a container vessel on its 23-day voyage from Singapore to Bremerhaven in Germany. Two tanks, one filled off Singapore and the other off Colombo, Sri Lanka, were monitored for their phyto- and zooplankton content by daily sampling. As already reported in previous studies, species abundance and diversity, especially of zooplankton, decreased sharply during the first days, and only a few specimens survived the whole cruise. The contents of the Colombo tank, however, changed dramatically during the last week. The harpacticoid copepod, *Tisbe graciloides*, increased its abundance by a factor of 100 from 0.1 to 10 ind. l⁻¹ within a few days. This is the first time that a ballast water organism has been found to multiply at such a high rate. Opportunistic species such as *Tisbe* are apparently able to thrive and propagate in ballast water tanks under certain conditions. Ballast water tanks may thus serve as incubators for certain species depending on their characteristics.

Introduction

Among the ways in which non-indigenous aquatic species cross their geographical borderlines and establish new populations in faraway areas and continents, the transport of ballast water in overseas traffic seems to play the key role. The pioneering research studies by Medcof (Medcof, 1975) and Carlton (Carlton, 1985) have shown that a large variety of animals, ranging from protists to fish, are able to survive as blind passengers in ballast water tanks for several weeks during transoceanic cruises. This finding has strengthened the suspicion that the discharge of ballast water originating from other oceanic regions is responsible for the invasion of alien species. This means of transport is especially probable for all kinds of plankton, including benthos and nekton organisms with a planktonic larval phase or a semipelagic mode of life.

The significance of ballast water as a main vector for the invasion of alien marine and freshwater species has already found official recognition through the International Maritime Organization (IMO). In view of the steadily increasing overseas traffic, and the larger size and higher speed of modern vessels, both of which favour the survival rate of the organisms, the IMO has formulated special regulations for reducing the transport of organisms, one of which is the exchange of water in the open ocean (IMO, 1995; Nauke, 1998).

Recent research has concentrated on two areas. The first is the assessment of non-indigenous species with special emphasis on their possible introduction by ballast water discharge. Such studies focus on harbour areas characterized by a high incidence of overseas traffic [e.g. (Carlton and Geller, 1993; Mills *et al.*, 1993;

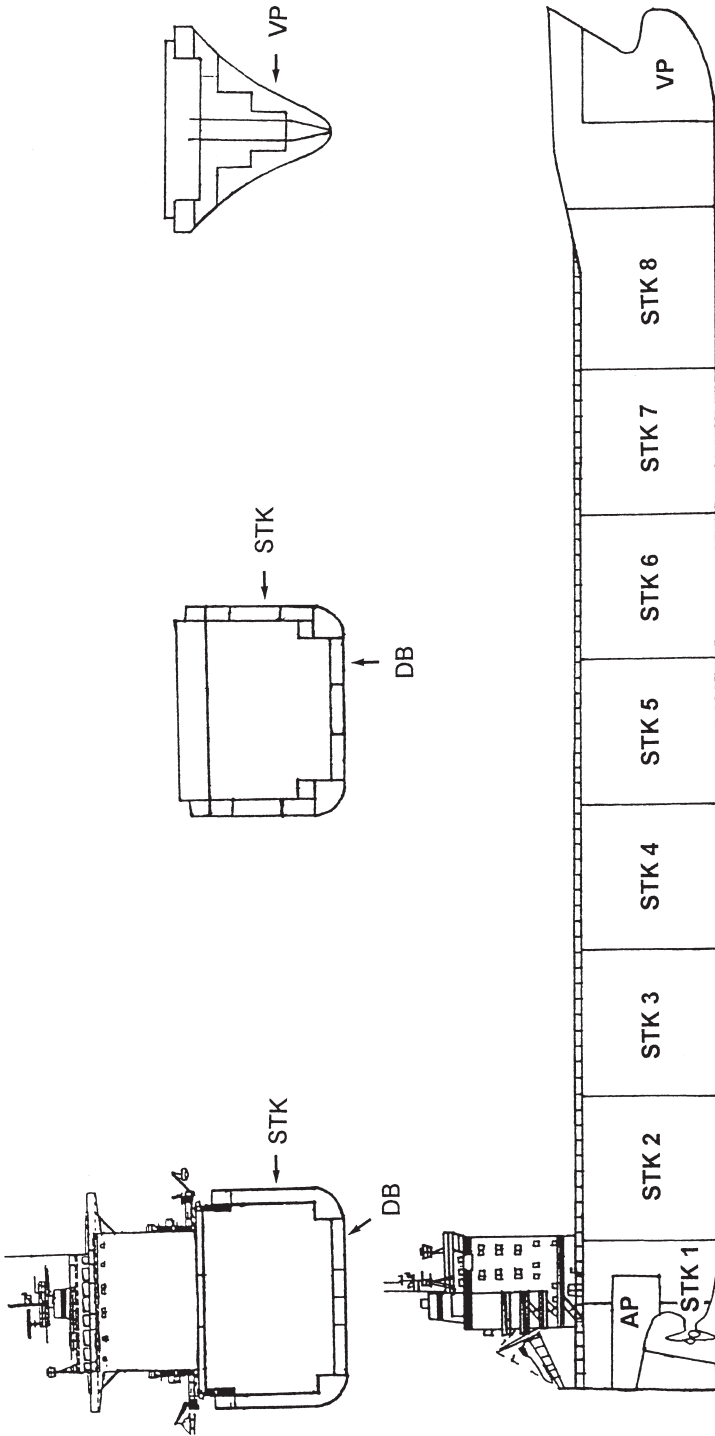


Fig. 1. Profile view of a modern container vessel showing the position of ballast water tanks (AP = aft peak tank, VP = fore peak tank, STK = side tanks and DB = double bottom tanks).

Eno *et al.*, 1997; Minchin and Sheehan, 1998)]. A recent overview is given by Ruiz *et al.* (Ruiz *et al.*, 1997).

The second field of investigation is the content and fate of living organisms in ballast water tanks and the environmental conditions encountered [e.g. (Hallegraeff and Bolch, 1991; Carlton and Geller, 1993; Subba Rao *et al.*, 1994; MacDonald, 1998)]. The present paper is a contribution to these investigations.

In 1992, a joint research project between the Institut für Meereskunde and the University of Hamburg, commissioned by the German Federal Environmental Agency, was launched to investigate the flora and fauna carried into German ports by international ship traffic. During this 4-year study, 189 vessels were investigated and a total of 334 samples taken (Gollasch, 1996; Gollasch *et al.*, 1998). Of the 404 botanical and zoological taxa found, about 60% comprised foreign organisms, non-indigenous in the Baltic or North Sea. During this project, a container vessel was accompanied from Singapore to Bremerhaven, Germany, in order to investigate the survival rate of tropical plankton organisms during their interoceanic voyage. The intention of this paper is to add more information on changing environmental conditions in ballast water tanks and on the survival rate of plankton organisms. This will help to evaluate the risk of unintentional import.

Method

The accompanied vessel 'DSR-America' was built in 1993 and has a transport capacity of 2400 containers. Its size is approximately 45 000 tons deadweight (DWT) and 34 000 gross register tons (BRT), with a length of 216 m, a beam of 32 m and a draught of 11 m. The maximum capacity of ballast water amounts to 14 860 t.

The vessel left Singapore on 3 May 1995, called at Colombo, Sri Lanka, on 11 May and left it the next day, passed through the Suez Canal on 16 May, called at Rotterdam on 25 May and ended its 23-day cruise the next day in the German port of Bremerhaven.

Figure 1 shows an outline of a modern container vessel with the location of the four monitored ballast water tanks, the fore peak and aft peak tank, as well as the starboard and portside tanks No. 4. The maximum capacity of the sampled tanks ranged from about 350 t (aft peak tank) to 680 t (side tanks).

The aft peak tank was filled after departure from Singapore in the Strait of Malacca on 3 May and the other three tanks after departing Colombo on 12 May. In the first case, sampling started on the filling day and in the second, on the day after filling. Every morning, samples were taken through opened manholes. All four tanks were monitored daily for environmental conditions. Samples for assessing phyto- and zooplankton abundance and species composition were also collected daily from two tanks, the aft peak tank filled off Singapore and the portside tank filled off Colombo. A storm period with Beaufort force 7 prevented plankton sampling in the aft peak tank on 21 May.

The environmental conditions in the ballast water were recorded with WTW probes for temperature, salinity, oxygen content and pH, together with sea surface temperature and wind force.

Phytoplankton and zooplankton were sampled or concentrated by quantitative plankton nets with a conical diameter of 20 cm and a mesh size of 10 µm and 55 µm, respectively.

Vertical net tows were carried out for qualitative plankton studies. The aft peak tank permitted a sampling depth of about 6 m. A net tow was not practicable in the portside tank because of its construction with several partition floors. Therefore, samples were taken with a bucket and poured through the nets outside the tank.

Quantitative samples were taken with 10 l buckets and concentrated with both nets. Water (100 l) was filtered for both phytoplankton and zooplankton. Phytoplankton was preserved in 4% buffered formalin and zooplankton in 70% ethanol. The specimens sampled were identified as far as possible and counted on board using a microscope (Hertel & Reuss) with a maximum magnification of ×480 and an Utermöhl counting chamber for phytoplankton, and a dissecting microscope (Leitz) and a Bogorov tray for zooplankton.

Results

Environmental conditions

Figure 2 shows the temperature records of the four ballast tanks and the sea surface temperature for comparison. During the first 11 days, the aft peak tank and sea surface exhibited the same high temperature between 30° and 31°C. In the Arabian Sea, the temperature started to drop and reached a minimum of 12°C, presumably in the Bay of Biscay. During the continuous temperature drop, the tank water followed the sea temperature with a time lag of one to two days. The adjustment was faster in the fore and aft peak tanks than in the side tanks.

The oxygen content of the ballast water ranged from 78 to 135% saturation (Figure 3). The aft peak tank showed the largest variation. The oversaturation was probably due to pitching and rolling of the vessel during periods of strong winds, as indicated at the bottom of the Figure. It is, however, difficult to explain at the end of the cruise.

Phyto- and zooplankton in the Singapore ballast water

The freshly sampled ballast water contained about 1 cell l⁻¹, representing a very low concentration of larger phytoplankton species (>10 µm), most of which were diatoms (Figure 4). Their abundance dropped rapidly by a factor of ~10 within the first 10 days and remained more or less constant at a very low level until the end of the cruise. The very few dinoflagellates disappeared in the same period, with the last single record on 16 May.

The main species composition is shown in Figure 5. It consisted of 30 diatom species. Among them was *Odontella sinensis*. This is notable, as a bloom of this southeast Asiatic species was observed in the North Sea for the first time in 1903, and ballast water was already suspected as the transfer medium (Ostenfeld, 1908; Nehring, 1998). Nine dinoflagellate species were found, including the potentially harmful genera *Dinophysis* and *Gonyaulax*, and the cyanobacteria *Oscillatoria*.

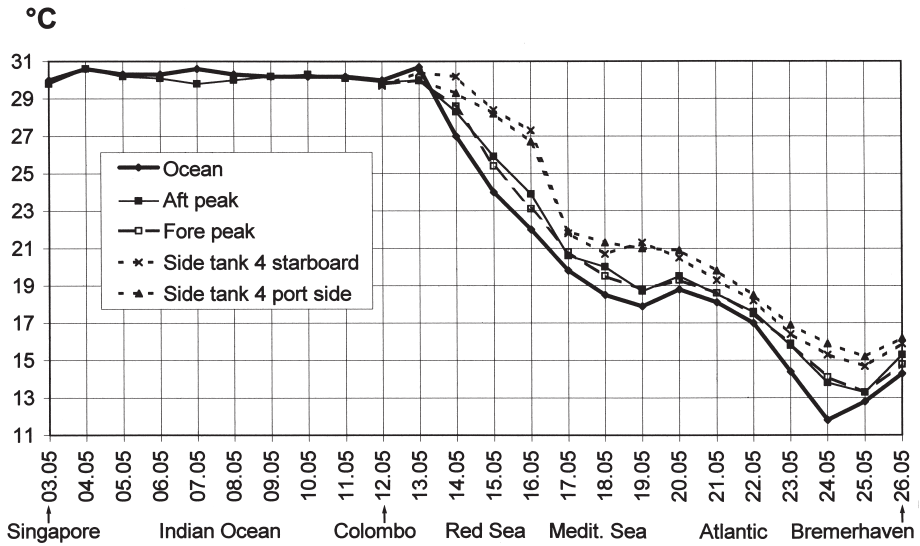


Fig. 2. Temperature of four different monitored ballast water tanks in relation to sea surface temperature during the cruise from Singapore to Bremerhaven, May 13–26, 1995.

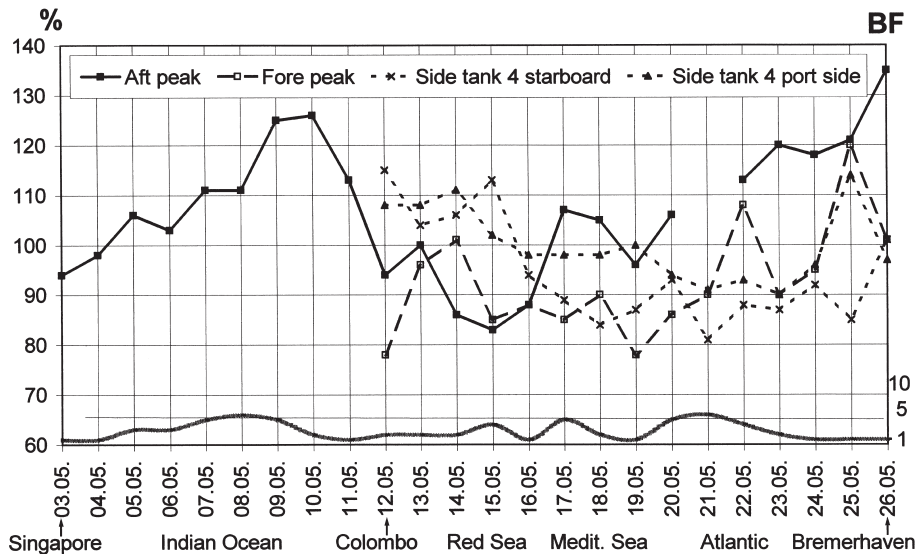


Fig. 3. Oxygen saturation (%) in four monitored ballast water tanks and mean wind force (BF).

Only four diatom species, *Pseudo-nitzschia seriata*, *Hemiaulus* sp., *Rhizosolenia* sp. and *Thalassiosira* sp., survived the whole journey, this being equivalent to 10% of all phytoplankton taxa recorded. The overall survival rate of phytoplankton specimens was only 0.2%.

The zooplankton community was dominated by juvenile and adult copepods

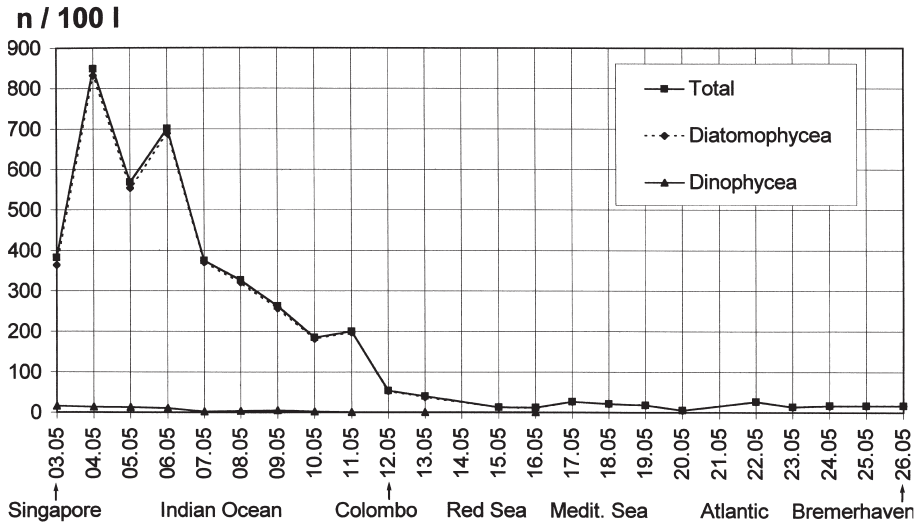


Fig. 4. Phytoplankton cells ($n\ 100\ l^{-1}$) recorded in Singapore ballast water (aft peak tank).

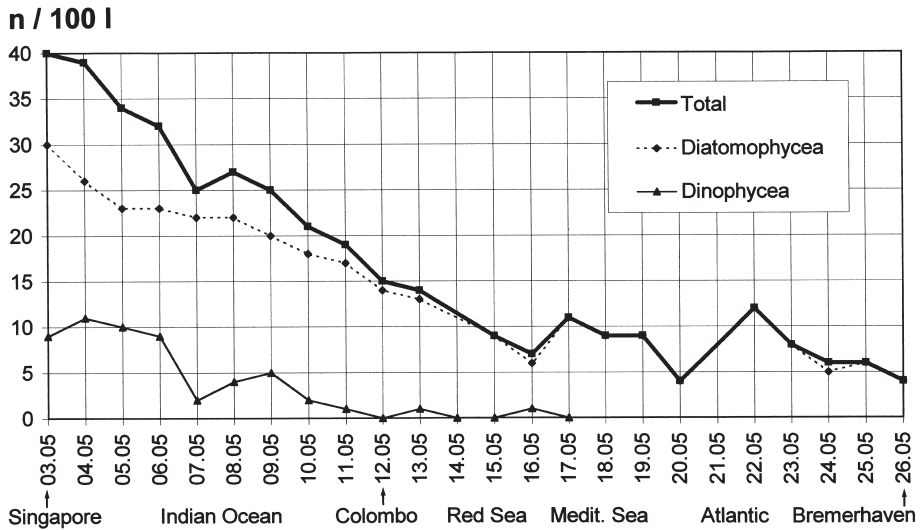


Fig. 5. Number of phytoplankton taxa ($n\ 100\ l^{-1}$) recorded in Singapore ballast water.

(Figure 6). The decrease in abundance after the tank was filled was even more pronounced than for phytoplankton. During the first four days, the abundance dropped by 90% and reached a minimum value on the eighth day which, with small variations, persisted until the end of the cruise.

Twenty-four taxa were initially recorded (Figure 7). The copepods were represented by 12 species, five calanoids (*Acartia plumosa*, *Eucalanus subcrassus*,

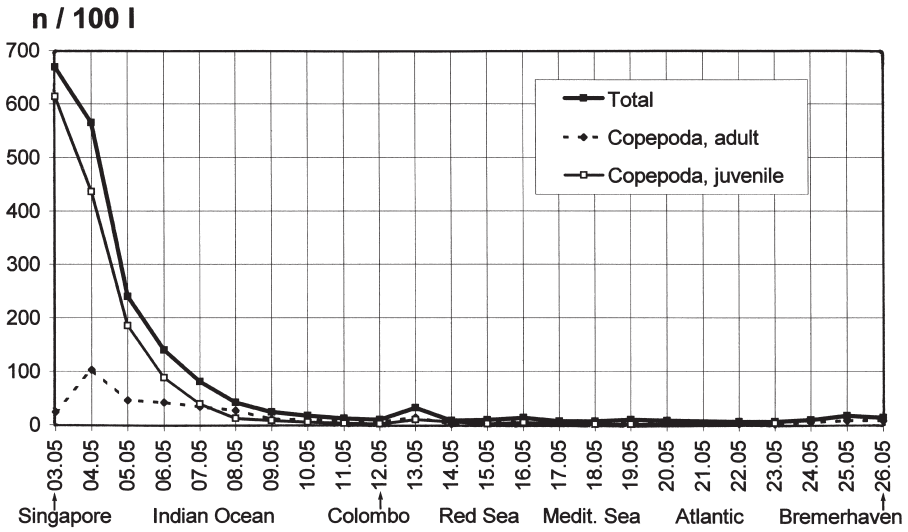


Fig. 6. Zooplankton individuals ($n\ 100\ l^{-1}$) recorded in Singapore ballast water (juvenile copepods = nauplii and copepodites).

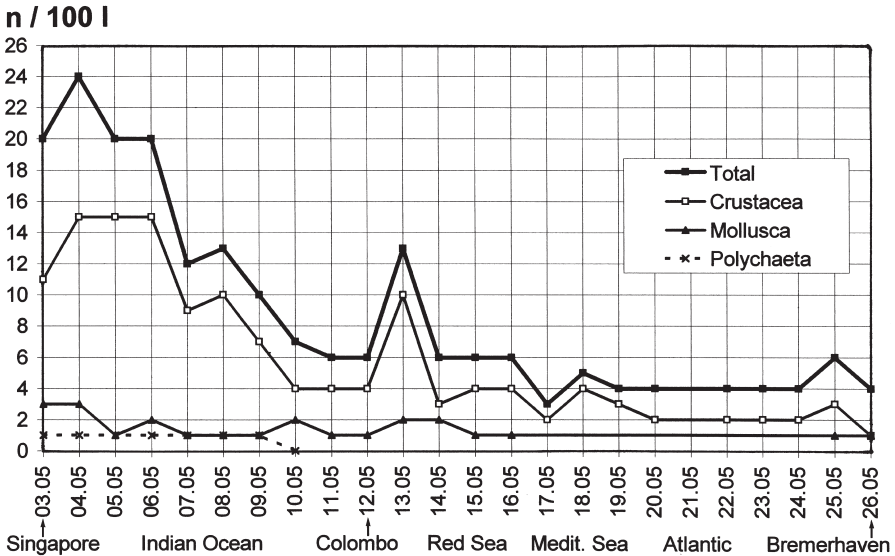


Fig. 7. Number of zooplankton taxa ($n\ 100\ l^{-1}$) recorded in Singapore ballast water.

Paracalanus parvus, *Temora longicornis* and *T. plumosa*), three harpacticoids (*Macrosetella gracilis*, *Microsetella rosea* and *Tisbe graciloides*), three poecilostomatoids (*Corycaeus ovalis*, *Oncaea venusta* and *Sapphirina intestinata*) and the parasitic *Monstrilla longiremis*. Few specimens (maximum 9 ind. $100\ l^{-1}$) were recorded for the following taxa: Chaetognatha, Siphonophora, Pteropoda

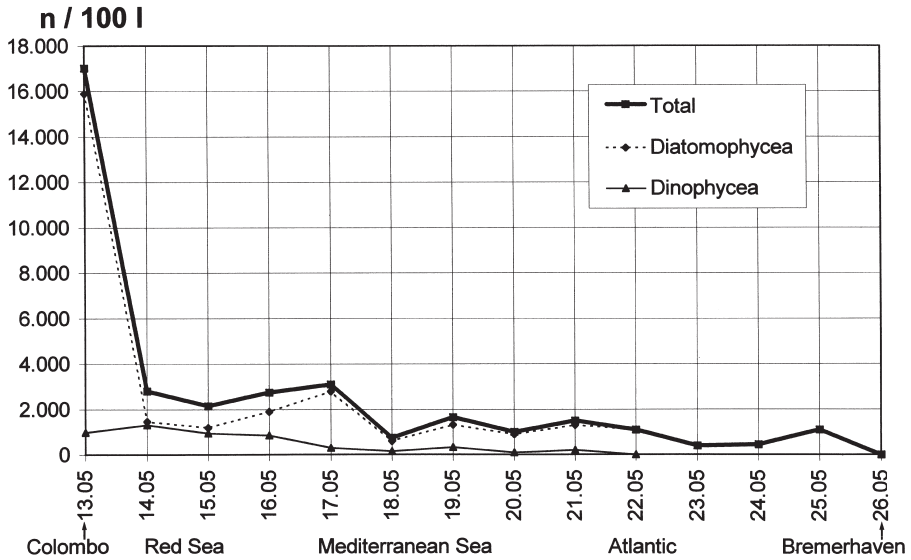


Fig. 8. Phytoplankton cells ($n\ 100\ l^{-1}$) recorded in Colombo ballast water (portside tank).

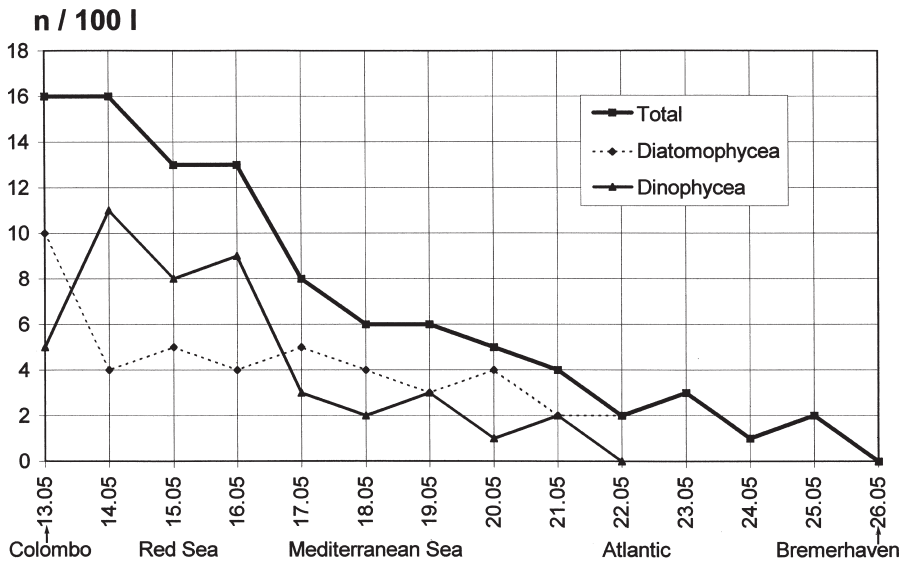


Fig. 9. Number of phytoplankton taxa ($n\ 100\ l^{-1}$) recorded in Colombo ballast water.

and Appendicularia, as well as larval stages of Decapoda, Gastropoda, Bivalvia, Polychaeta, Turbellaria and Pisces. Of the 24 taxa initially recorded, only four (17%) survived the 23-day cruise. These were several specimens of the harpacticoid copepod, *Tisbe graciloides*, and larvae of a turbellarian, gastropod and bivalve species. The overall survival rate of zooplankton specimens was 2%.

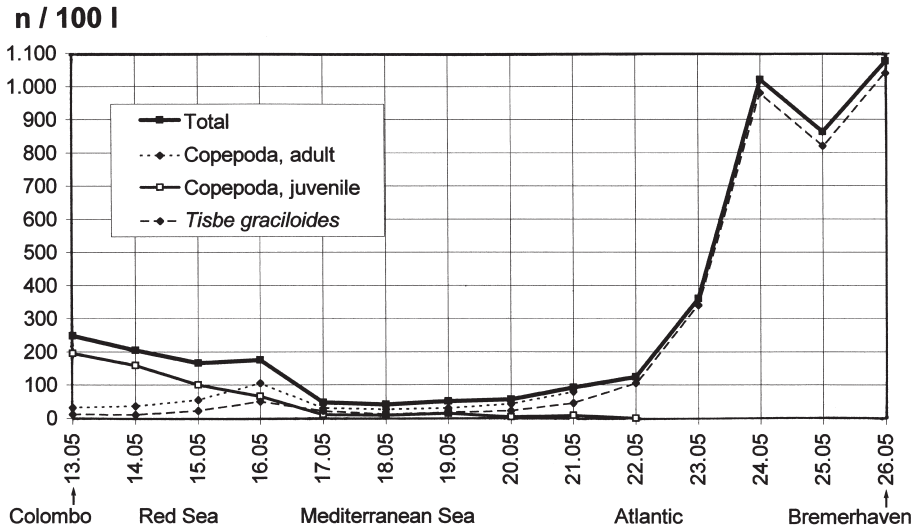


Fig. 10. Zooplankton individuals ($n\ 100\ l^{-1}$) recorded in Colombo ballast water (juvenile copepods = nauplii and copepodites).

Phyto- and zooplankton in the Colombo ballast water

The initial phytoplankton abundance, recorded one day after the tank was filled, was much higher than in the Singapore ballast water but in absolute terms, relatively low with a maximum of $17\ cells\ l^{-1}$ (Figure 8). As in the first tank, diatoms exhibited a strong dominance over dinoflagellates. A surprising feature was the very steep drop from day 2 to 3, followed by a second drop between days 6 and 7. The last dinoflagellates were recorded on day 10 and the last diatoms on day 13, one day before arrival in Bremerhaven.

Of the 16 species recorded (Figure 9), 10 were diatoms, five were dinoflagellates and one was a chrysophyte. The last living dinoflagellate cells recorded were *Blepharocysta* sp. and *Podolampas* sp., and among the diatoms, *Coscinodiscus* sp. and *Hemiaulus* sp.

Zooplankton abundance presented a completely different picture to the Singapore tank (Figure 10). The initial concentration was considerably lower and exhibited only a slight decrease until day 5 when it dropped by about 70% and then remained almost constant until 20 May. From then onwards, an almost exponential increase of the harpacticoid copepod, *Tisbe graciloides*, followed within only 4 days, reaching a maximum of $10.4\ ind.\ l^{-1}$ on the last day of the cruise.

Species diversity declined gradually from 16 to six species (Figure 11). Altogether, 21 taxa were recorded. The survival rate for the 14-day cruise was thus 29%. The majority of the zooplankton was again made up by 11 copepod species with three calanoids (*Calanus tenuicornis*, *Paracalanus parvus* and *Pseudochirella obtusa*), four harpacticoids (*Macrosetella gracilis*, *Microsetella rosea*, *Tisbe graciloides* and *T. furcata*) and four poecilostomatoids (*Copilia mirabilis*,

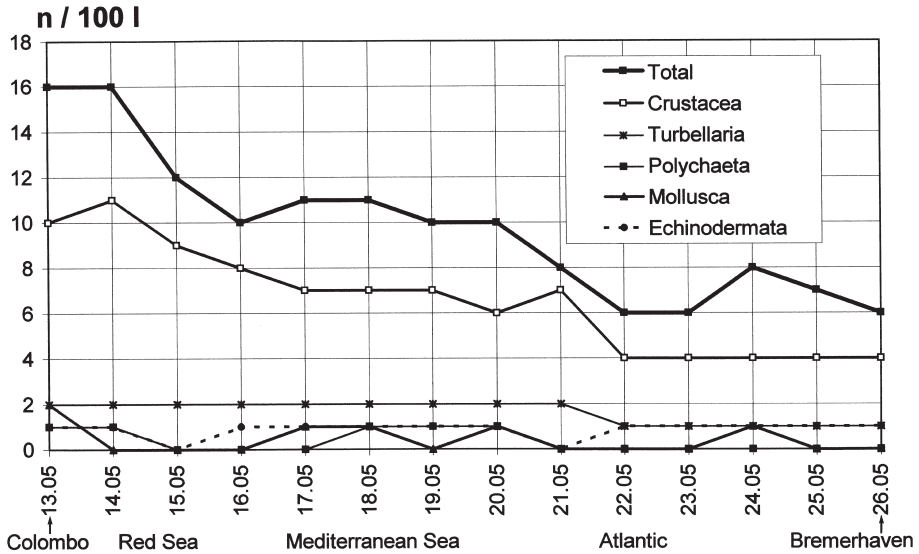


Fig. 11. Number of zooplankton taxa (n 100 l^{-1}) recorded in Colombo ballast water.

Corycaeus ovalis, *C. flaccus* and *Oncaea venusta*). The other taxa recorded in low numbers were Appendicularia, Chaetognatha, Rotatoria, Turbellaria and larvae of Decapoda, Bivalvia, Gastropoda, Polychaeta, Turbellaria and Echinodermata. The four harpacticoid species survived until the end of the 14-day cruise. Except for the dramatic increase of *Tisbe graciloides*, the abundance of all other species declined, resulting in a survival rate of 15%.

Discussion

In addition to the import of foreign species through aquaculture enterprises and hull fouling, ballast water exchange is regarded as the main vector for the introduction of non-indigenous aquatic organisms [e.g. (Medcof, 1975; Howarth, 1981; Carlton, 1985, 1987; Williams *et al.*, 1988; Pollard and Hutchings, 1990; Jones, 1991; Hallegraeff and Bolch, 1991; Rigby *et al.*, 1993; Subba Rao *et al.*, 1994; Smith, 1995; Gollasch, 1996)]. In all these studies, a large number and variety of living organisms was recorded in ballast water tanks. Very little, however, is known about the survival rate of ballast water organisms during their transport as there are only a few reports on the fate of ballast water organisms during transit (Carlton, unpublished data; Rigby and Hallegraeff, 1993, 1994; Fukuyo *et al.*, 1995).

Temperature and oxygen content in the tanks, as well as sea surface temperature and wind force, were regarded as the main environmental conditions affecting the ballast water organisms. Sea surface temperature principally governs the temperature in tanks, but there is a distinction between the temperature adaptation of the fore peak and aft tank as opposed to the side tanks. The former followed the

sea surface temperature relatively regularly with a more or less constant difference of 1°C plus, whereas the side tanks deviated to a much larger extent with differences between 2 and 5°C as an extreme value on 16 May (Figure 2). The explanation is that the upper parts of the side tanks extend over the sea surface level and are thus sun-exposed, causing the ballast water to warm up (Figure 1).

The oxygen content varied between an undersaturation of 78% and an oversaturation of 135%. The ballast water tanks were not filled up to the rim and from the two tanks sampled for plankton (the aft peak and portside tank), 200 l water were removed every day. The overlying air volume could have caused the oversaturation through mixing with the water during periods of strong winds, when the vessel was pitching and rolling.

It is interesting to note that the environmental conditions in the tanks were apparently not responsible for the sudden decline of organism abundance shortly after the tanks were filled. The only plausible explanation is that the generally delicate plankton organisms suffered damage during the filling of the tanks through contact with the impellers of the pump and tank walls and died within a few days. Wave action inside the tanks may have further injured the organisms. Darkness may have affected phytoplankton by preventing photosynthesis, leaving only the mixo- or heterotrophic mode of nutrition.

The gradual decline in temperature during the second half of the cruise may also have affected some stenotherm warm-water species, although an adaptation from warm to cold water is physiologically easier than vice versa. In the Colombo tank, for example, the tropical/subtropical harpacticoid copepod species *Macrosetella gracilis* and *Macrosetella rosea*, survived until the end of the cruise. Crustaceans seem to be generally hardier than very delicate organisms such as siphonophores, appendicularians and chaetognathes, which survived only a few days. An intermediate position was occupied by polychaete, bivalve and echinoderm larvae, which survived for 7 to 14 days.

Our investigation confirmed the general rule that abundance and species diversity of plankton decreases with the length of the confinement of the organisms in the tanks. This rule was established by the observation that an inverse relationship exists between the occurrence of plankton organisms and the age of the ballast water (Carlton, 1985; Williams *et al.*, 1988). This rule is only valid for plankton organisms and not for benthos, which is apparently able to live in ballast water tanks for long periods. The benthic amphipod, *Corophium acherusicum*, found after 116 days of confinement (Gollasch, 1996), is an example of such a long survival.

One exception, however, is our observation of an increase in a species in a ballast water tank, i.e., *Tisbe graciloides* in the Colombo water. This is the first record of such a spectacular increase. The harpacticoid genus, *Tisbe*, is generally well known as it contains a number of species with cosmopolitan distribution, opportunistic feeding behaviour, fast growth and high reproduction. For this reason, several species were chosen as promising candidates for laboratory mass culture, e.g. *Tisbe holothuriae* (Hoppenheit, 1976; Zhang and Uhlig, 1993). Most of the *Tisbe* species are omnivorous, feeding on a large variety of food such as algae, bacteria, detritus and artificial fish feed (e.g. Tetramin), and also

scavenging on dead animals (Hicks and Coull, 1983). A ballast water tank with dead plankton would thus provide plenty of food. *Tisbe* species are generally epibenthic or semipelagic.

Tisbe graciloides (Sars, 1920), after Lang (Lang, 1948), is not as well known as other species, but as the better studied members of this genus have many characteristics in common, it seems justified to assume that *T.graciloides* will share these, too. Although the development cycle consists of the six naupliar and five copepodite stages typical of copepods, it passes through these stages very rapidly. The minimum period reported for *Tisbe* sp. at 18°C is 4 days from hatching to adult (Hicks and Coull, 1983). This would correspond to a development time of about 7 days from egg to adult; Hoppenheit reports 7.9 days from egg to adult female of *T.holothuriae* at optimal culture conditions at 22°C (Hoppenheit, 1976).

Tisbe species, e.g. *T.furcata* and *T.holothuriae*, have a mean egg number of 50 per egg sac or clutch, and can produce 6–10 clutches after one copulation, demonstrating a high reproductive rate (Hicks and Coull, 1983). Alongi raised *T.holothuriae* under optimal conditions at 20°C in Petri dishes and obtained, in a mixed population, an increase from 10 ind. 10 cm⁻² to 115 ind. 10 cm⁻² within 10 days (Alongi, 1985). This means that a population could double within about 3 days.

Lopez (Lopez, 1982) studied the dynamics of a *T.cucumaria* population in a holding tank of a seawater providing system where it lived under almost natural conditions. In analysing its population dynamics, the author states that the density of the organisms may pass through the following four characteristic states: 'maintenance' with low density, 'colonization' of a nutrient-rich site, 'bloom' with intensive reproduction resulting in very high density, and 'dispersal' with emigration. It is possible that we observed such a bloom phase in the Colombo tank.

Miliou (Miliou, 1993) investigated the influence of various light/dark cycles on the culture of *T.holothuriae* and obtained the interesting result that the mortality rate was lowest in complete darkness and the sex ratio (female/male) with 65% highest. This could be an additional point favouring growth conditions in a ballast water tank.

Another interesting point which may explain the exponential rise in abundance of *T.graciloides* is the active emergence of small benthic copepods, as thoroughly investigated by Walters (Walters, 1991) in Tampa Bay on the coast of Florida. One of the most common harpacticoid copepods was *T.furcata*. The emergence into the open water was studied by means of small traps consisting of an acrylic tube placed on the sea bottom for a 2-hour period, pre- and post-sunset and pre- and post-sunrise, during the course of the year. The results showed that the highest emergence rate from the ground into the open water occurred after sunset, reaching a maximum of 44% of the total population of *T.furcata*. Most of the emerging individuals were adults and a smaller portion were late copepodite stages. There is some evidence that this emerging and swimming in open water indicates mating behaviour (Bell *et al.*, 1988).

In critically evaluating our own observation, we have to assume that our sampling method by means of a bucket was only able to record an unknown portion of the epibenthic or semipelagic population of *Tisbe*. A decreasing

number of copepod nauplii was observed from 197 ind. 100 l^{-1} on the first day to 1 ind. on the 7th day (Figure 10). Unfortunately, it was not possible to identify these nauplii to the species level, as this is very difficult. It must be stated that *T.graciloides* was also present in the Singapore ballast water and survived there until the end of the cruise. It was also recorded in the tanks of six other vessels during our study. The origin of the respective ballast water was, in five instances, the Far East (Japan, China, Malaysia) and in one, the Levantine Sea in the Mediterranean (Gollasch, 1996).

The difference between the tanks, the aft peak tank filled at Singapore and the portside tank filled at Colombo, needs to be addressed. Their construction differed, with the portside tank having several partition floors which could have favoured the sedimentation of phytoplankton and provided better living conditions for *Tisbe*. The phytoplankton concentration was also much higher in the Colombo tank than in the Singapore tank, as shown by Figures 4 and 8.

The exponential increase observed within 4 days (20–24 May in Figure 10), with a rise from 37 to 975 ind. 100 l^{-1} , comprised mainly late copepodite stages and adults. It coincided with a steadily increasing number of egg-bearing females from 5 to 78 ind. 100 l^{-1} . It therefore seems reasonable to assume that we were observing a bloom phase of the population as a result of a strong propagation due to optimal feeding conditions in the tank. The population bloom, as observed by our sampling, was probably caused by the emergence of young adults from the tank bottom during the course of mating and reproduction behaviour.

In summary, we would like to emphasize that at least semiplanktonic organisms, such as harpacticoid copepods, are able to thrive and reproduce in ballast water tanks. A ballast water tank can thus function as an incubator during the cruise for some species. This fact may have some impact on the release of non-indigenous species in the destination harbour or in near-coastal waters where the ballast tanks are emptied. Further ship-accompanying investigations are therefore required to gather more information on whether this observation should be recognized as a rare exception or as a frequently occurring event.

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