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Breaking the ice: the introduction of biofouling organisms to Antarctica on vessel hulls

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ABSTRACT

1. Few reports exist that describe marine non-native species in the Southern Ocean and near-shore waters around the Antarctic continent. Nevertheless, Antarctica's isolated marine communities, which show high levels of endemism, may be vulnerable to invasion by anthropogenically introduced species from outside Antarctica via vessel hull biofouling.

2. Hull surveys of the British Antarctic Survey's RRS James Clark Ross were undertaken between 2007 and 2014 at Rothera Research Station on the Antarctic Peninsula (Lat. 67°34'S; Long. 68°07'W) to investigate levels of biofouling. In each case, following transit through scouring sea-ice, over 99% of the vessel hull was free of macroscopic fouling communities. However, in some surveys microbial/algal biofilms, balanomorph barnacles and live individuals of the cosmopolitan pelagic barnacle, *Conchoderma auritum* were found in the vicinity of intake ports, demonstrating the potential for non-native species to be transported to Antarctica on vessel hulls.

3. Increasing ship traffic volumes and declining duration of sea ice in waters to the north and west of the Antarctic Peninsula mean the region may be at increased risk of non-native species introductions. Locations at particular risk may include the waters around popular visitor sites, such as Goudier Island, Neko Harbour, Whalers Bay, Cuverville Island and Half Moon Island, and around northern peninsula research stations.

4. Simple and cost-effective mitigation measures, such as intentionally moving transiting ships briefly through available offshore sea ice to scour off accessible biofouling communities, may substantially reduce hull-borne propagule pressure to the region. Better quantification of the risk of marine non-native species introductions posed by vessel hulls to both Arctic and Antarctic environments, as sea ice patterns and shipping traffic volumes change, will inform the development of appropriate regional and international management responses.

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KEY WORDS: marine bioinvasion; alien species; shipping; invertebrates; introduction; climate change; dispersal; polar regions; sea ice

INTRODUCTION

Antarctic marine benthic environments contain the majority of the region's life and some of the

most biodiverse habitats on Earth (De Broyer *et al.*, 2014). Up until the mid-20th century, when permanent human settlement of the continent began, predominantly for scientific research purposes, the

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Antarctic marine environment had little direct exposure to anthropogenically introduced non-native species. However, these isolated marine ecosystems, with high levels of endemism, may be particularly susceptible to the impacts of invasive species (Lodge, 1993). The geographical isolation of Antarctica and the existence of the Antarctic Circumpolar Current present considerable barriers to species movement to the region, but physiological constraints may also reduce species survivorship and subsequent establishment and invasion of the polar marine environment (Barnes *et al.*, 2006). Recent reports have highlighted the ongoing colonization and invasion of terrestrial communities in the sub-Antarctic, and increasingly the Antarctic continent (Frenot *et al.*, 2005; Hughes *et al.*, 2015), but, as yet, only a single non-native species has been recorded from within the Antarctic marine environment (Clayton *et al.*, 1997). Increasing marine traffic, including private yachts and military, national operator, fishing and tourist vessels, in the waters around Antarctica may increase the risk of non-native species introductions (Lynch *et al.*, 2010; COMNAP, 2015; IAATO, 2015a).

Ballast water and hull biofouling constitute the two main anthropogenic vectors for marine species transportation to Antarctica, although species transport via anthropogenic and natural marine debris is recognized as a passive vector in the region (Barnes, 2002). Ballast water is considered a minimal threat because vessels rarely release ballast water in the region, but rather take on ballast water following unloading of cargo at Antarctic research stations (Lewis *et al.*, 2003). Furthermore, specific ballast water management guidelines for use within Antarctic waters have been put in place by the International Maritime Organisation's (IMO) Marine Environment Protection Committee (MEPC) (Resolution MEPC.163(56); July 2007). In contrast, southward transport of fouling species on vessel hulls is considered a potentially greater risk, particularly as polar vessels may over-winter in more northerly warmer water ports where fouling communities may develop on their hulls (Lewis *et al.*, 2003; Lee and Chown, 2009). Given the diversity of home ports, anti-fouling management practices, and routes and duration of voyages taken by these vessels, the diversity of transported non-native species and propagule

pressure is likely to be highly variable, and as yet remains unquantified (Lewis *et al.*, 2003).

A significant factor reducing propagule pressure of marine biofouling species being introduced to polar regions is considered to be the scouring effects of sea ice on vessel hulls that may remove adhered species. However, there is little evidence to show the effectiveness of this natural process at reducing species translocation, particularly as niche areas such as sea chests, bow thrusters, propeller shafts and inlet gratings may not be subject to ice abrasion. Furthermore, Arctic and Antarctic sea ice thickness and extent varies year to year and generally declines as the summer season proceeds (Stroeve *et al.*, 2008; Parkinson and Cavalieri, 2012; Stammerjohn *et al.*, 2012), so the associated hull scouring effects cannot be relied upon to reduce the risk of introduction of invasive species. While the IMO adopted the '*Guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species*' through the MEPC in July 2011 (Resolution MEPC.207(62)) to raise biofouling management standards, the guidelines contain no specific measures regarding fouling management in polar locations.

Four hull surveys of a British Antarctic Survey (BAS) ice-strengthened ship following its transit to Antarctica through sea ice from the United Kingdom via South American and/or South Atlantic ports were undertaken. The aim was to assess the presence and extent of hull fouling biota, and in particular to evaluate the scouring effects of sea ice.

MATERIAL AND METHODS

The BAS research vessel RRS James Clark Ross (JCR) provides science and logistical support for BAS activities and makes an annual return voyage from the UK to the Antarctic, lasting approximately eight months. En route, the ship may visit ports in the South Atlantic and South America, although time in port is generally restricted to a few days. On arrival in the Southern Ocean the ship may visit UK research stations in South Georgia, the South Orkney Islands and the Antarctic Peninsula, as well as undertaking scientific cruises and other logistic activities. Owing to the relatively southerly

location of the UK's Rothera Research Station (67°34'S; 68°07'W), compared with the majority of national stations and visitor sites on the Antarctic Peninsula, the vessel may pass through varying amounts of both fast and pack ice during its voyage (Figures 1, 2).

The hull of the JCR was surveyed by members of the Rothera Research Station dive team using scuba in December 2007, December 2010, January 2014 and December 2014 upon its first arrival at the station each austral summer. The JCR is approximately 95 m in length and has a full load draft of 6.4 m; the wetted surface area of the hull is 2645 m². On each occasion, a visual survey of the port side of the hull was undertaken by two divers along a transect of the vessel extending from the stern towards the bow. Particular attention was paid to 'niche areas' including the rudder, propeller, sea-chests, intakes, outflows, thrusters and central underside of the hull. Scaled photographs were taken of all niche areas and any fouling organisms encountered, and used to estimate the area of the hull covered by

macroscopic organisms. Fouling organisms on the hull were collected for identification, where accessible.

RESULTS

Before each survey the vessel had been dry-docked four to five months earlier and painted with self-polishing copolymer antifoulant, the only exception being the January 2014 survey, when the hull was last painted 17 months earlier. Surveys showed that hull surfaces that were exposed to ice were scoured clean of biota, with the antifoulant paint also removed particularly along the waterline where ice impact levels are high. However, in small niches that are protected from ice, such as around intake ports and sea chests, fouling by a microbial/algal biofilm was recorded during all four surveys. Furthermore, collective macroscopic biofouling in niche areas on one side of the vessel was 1 m² in December 2007 and 0.1 m² in December 2014 (equivalent to 0.2 and 0.02% of the ship hull, respectively). During the December 2007

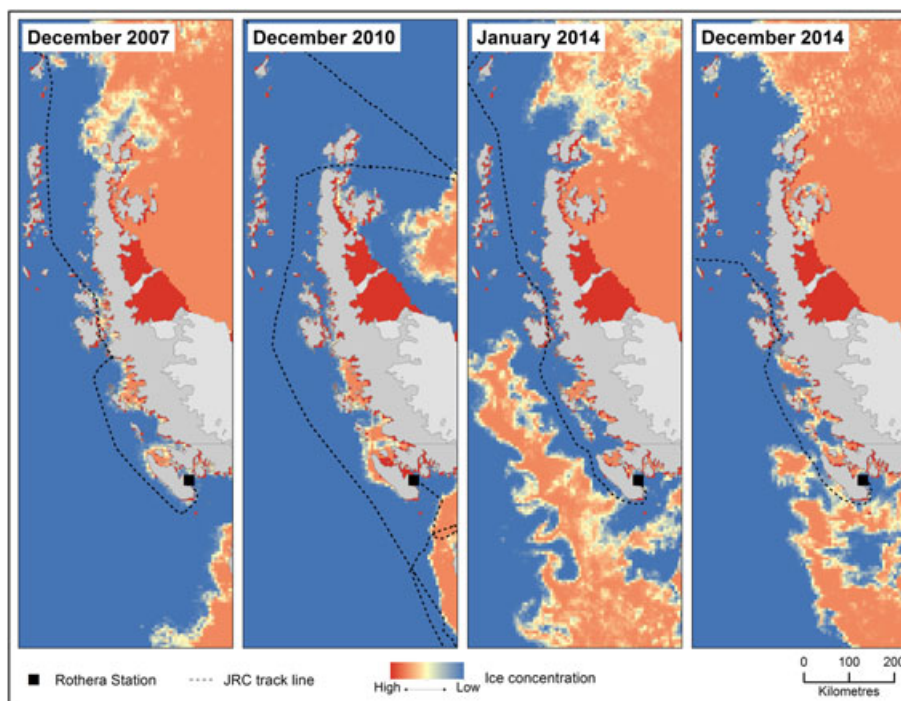


Figure 1. Sea ice conditions experienced on the voyage of the RRS James Clark Ross before arrival at Rothera. Permanent ice shelves are shown in dark red. Ocean colour indicates sea ice concentration (orange indicates high sea ice concentration, while blue indicates little or no sea ice). Sea ice data imagery was obtained from Polar View (<http://www.polarview.org/>). Note that most of the waters off the northern Antarctic Peninsula are free of sea ice at this time, giving easier access to stations and visitor sites in this region (Figure 2).

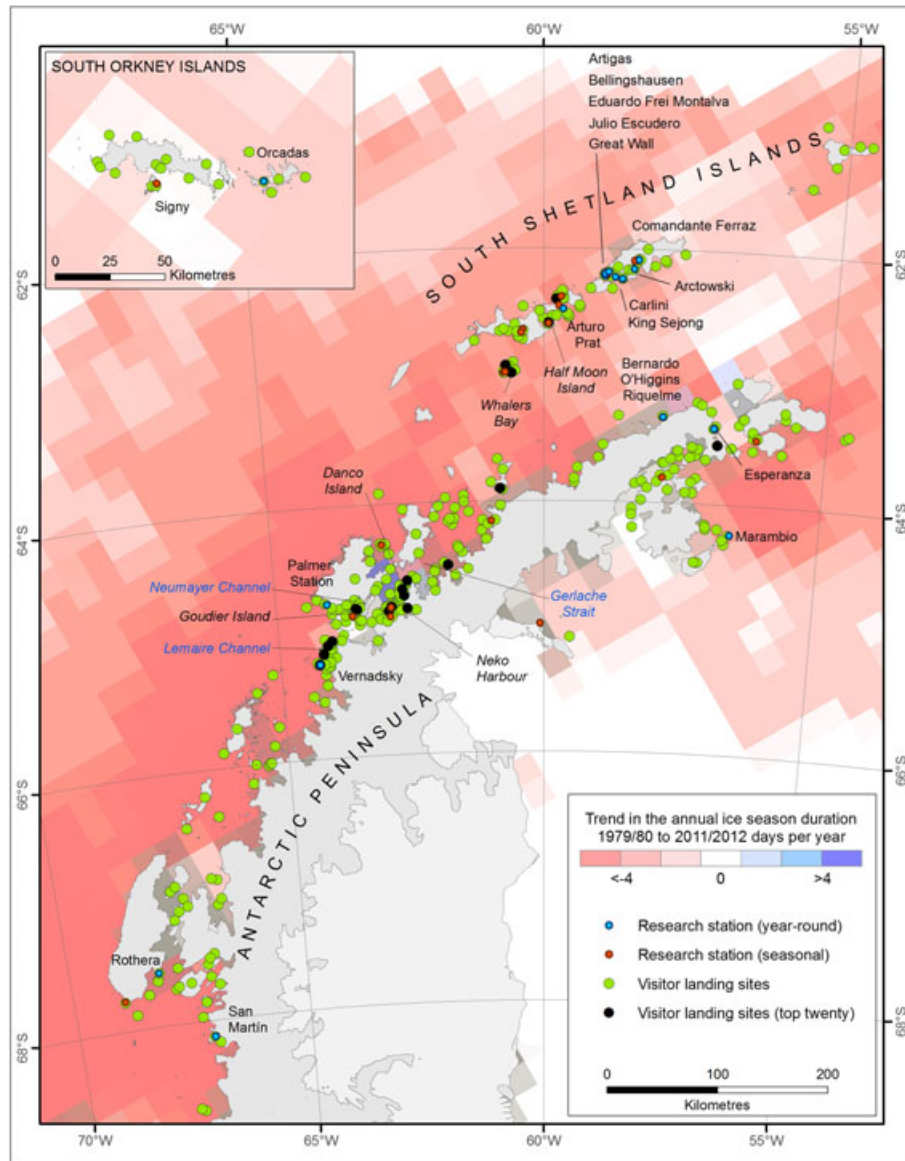


Figure 2. Map of the Antarctic Peninsula region showing the research station locations and tourist visitor landing sites. Data showing the trend in annual sea ice duration (provided by S. Stammerjohn, University of Colorado, Boulder) reveal a rapid decrease in annual sea ice duration over much of the ocean to the west of the Antarctic Peninsula (i.e. the pink colouration; coastal grey squares indicate areas for which no data are available). The area of sea ice duration decline coincides with the area where most human activity occurs in the region, with most of the national operators and the tourism industry relying heavily upon ships for resupply and/or transportation throughout the austral summer season.

survey, microbial/algal biofilms were observed on intakes grates; acorn barnacles were found in two locations; and goose-neck barnacles (probably *Conchoderma auritum* (L.)) were identified attached to one intake. In December 2014, *C. auritum* were again observed in one of the hull intake ports ($n < 20$). On this occasion the largest individuals could be collected (three specimens, size range: 8.9–12.9 mm (capitulum

length), 18.6–29.4 mm (total length)) and, upon examination in the laboratory, all were found to be alive.

DISCUSSION

The methodology did not allow direct estimation of the decline in vessel fouling as a result of sea ice

abrasion, as surveys showing the extent of fouling before the vessel entered the Southern Ocean were not possible. However, the complete lack of biofouling on the exposed hull surface during any of the surveys, coupled with direct observational evidence of sea ice impacts on the vessel hull, suggests sea ice scour is effective at removing microbial/algal and macroscopic organisms from the outer hull and therefore has the potential to reduce marine non-native species propagule pressure (Lewis *et al.*, 2004). In contrast, a survey of vessels travelling through waters within the Canadian Arctic, where ice scouring was possible but not confirmed, showed substantially greater levels of biofouling and fouling community diversity (Chan *et al.*, 2015).

As far as we are aware, this study of biofouling of a polar research vessel is the first to report observations of the presence of hull fouling species by divers within the Antarctic Treaty area (i.e. the area south of latitude 60°S). In another investigation of Antarctic vessel fouling, Lee and Chown (2007) demonstrated that the invasive mussel, *Mytilus galloprovincialis*, had survived transportation to the Antarctic region within the two sea chests of the SA 'Agulhas'. The two sea chest's total internal surface area was *c.* 42 m², with 60–65% of this fouled, giving an approximate total fouled area of 26 m², equating to *c.* 1% of the ship's hull. Consequently, ship hull design may be an important factor in determining the colonizable area that is unaffected by ship transit through sea ice.

Live macroscopic fouling organisms were found in two of the four hull surveys. Overall, biodiversity was low with only two macrobiotic organisms present: *Conchoderma auritum* and balanomorph barnacles. *Conchoderma auritum* is a cosmopolitan fouling organism, generally found on sessile barnacles (e.g. *Coronula* sp.), on baleen whales or the teeth of sperm whales and other toothed cetaceans (Newman and Abbott, 1980), but has also been described from ship hulls and various abiotic floating materials (Lewis *et al.*, 2004). While the discovery of *C. auritum* may be of little ecological concern, analysis of the specimens may give some clue regarding the potential for non-native species introductions to Antarctica from beyond the Southern Ocean.

Conchoderma auritum has been described as reproductively inactive at high latitudes (Newman and Abbott, 1980), but elsewhere rapid growth of stalked barnacles has been noted (Eckert and Eckert, 1987), with individuals of *Conchoderma* spp. achieving a capitulum size of 20 mm after only 17 days in warmer water conditions (18–25°C; MacIntyre, 1966). The source of the individuals found on the JCR cannot be known, but the voyage history of the vessel (i.e. from the United Kingdom to the South Atlantic and then across the Southern Ocean to the Antarctic Peninsula) suggests that the source is likely to be greater than 2000 km from Rothera Research Station and potentially outside of the Southern Ocean (as was reported for *M. galloprovincialis* by Lee and Chown, 2007). Acorn barnacles found during the survey in 2007 were not identified further owing to the restricted access; however, no shallow benthic balanomorph barnacles are known from the Antarctic continent (Newman and Ross, 1971), making it likely that these specimens were non-native. If live acorn barnacles were confirmed on ship hulls in the region, the potential for the introduction of a novel Order (Sessilia) to Antarctica would be a significant concern.

Which locations may be at particular risk of marine non-native species introduction?

The Antarctic Peninsula contains >50% of the continent's coastal research stations (COMNAP, 2015) and is the focus for *c.* 95% of Antarctica's ship-borne tourism (IAATO, 2015a) (Figure 2). Over the past 25 years, levels of tourist vessel traffic around the northern and western Antarctic Peninsula region have increased greatly. The highest concentrations of tourist ship traffic have been reported from the Gerlache Strait/Errera Channel, Neumayer Channel/Peltier Channel and the Lemaire Channel/Penola Strait regions (Lynch *et al.*, 2010). Furthermore, the terrestrial visitor sites at Goudier Island, Neko Harbour, Whalers Bay, Cuverville Island and Half Moon Island all experienced more than 100 landed visits during the 2014–2015 season, where ships may stop for several hours while tourists go ashore, creating the opportunity for marine non-native species to be introduced to near-shore

waters (IAATO, 2015b). Coastal Antarctic locations used for cargo off-load to resupply research stations may also be at substantial risk from hull-borne non-native species (Figure 2). In contrast to the rapid site visit itineraries generally followed by tourist ships, military/national operator vessels may be moored at home ports and Antarctic locations for prolonged periods, allowing more opportunity for attachment and later dispersal of fouling species. Thus, all of the aforementioned highly visited and/or transited locations may be at increasing risk of non-native species introductions via ship hulls. Supporting this assessment, it is notable that the only non-native species known within the Antarctic Treaty area (i.e. the alga *Enteromorpha intestinalis*) was reported from Half Moon Island (62° 37'S; 59° 57'W) and Deception Island (62° 59'S; 60° 34'W), which are both in the top five most tourist visited sites in Antarctica, but are also visited by national operator vessels (Clayton *et al.*, 1997).

Sea ice abrasion of vessel hulls – good or bad?

Sea ice abrasion of hulls may have both a positive and negative effect on the risk of introduction of non-native species. Scouring effects are likely to be rapid once sea ice is encountered, and fouling communities may be removed over large areas of the hull. However, it was noted that anti-fouling treatments were often scoured from the exposed hull by ice, and in particular along the waterline. As a result, ships making multiple voyages to and from the region through sea ice during the early austral season may be more likely to have fouling organisms attached later in the season when little or no sea ice is present to remove further fouling communities (Lewis *et al.*, 2004; Argentina, 2015). This may further increase the risk of non-native species being carried to the Antarctica Peninsula region on hull surfaces later in the austral season, and the effect may be further exacerbated by sea ice decline linked with regional climate change (Parkinson and Cavalieri, 2012; Stammerjohn *et al.*, 2012) (Figure 2). Importantly, trends in sea ice duration and extent are not consistent in all areas of the Southern Ocean and the implications for propagule pressure via vessel hulls in areas of the Southern Ocean and coastal Antarctica

outside the western Antarctic Peninsula region may be starkly different (Stammerjohn *et al.*, 2012; Holland, 2014).

CONCLUDING REMARKS

The Antarctic Treaty Consultative Meeting, which governs activities within the Antarctic Treaty area, has produced or endorsed guidelines for reducing the risk of non-native species introductions predominantly in terrestrial environments (CEP, 2011). However, management strategies and technologies for reducing marine non-native species introductions to the region associated with vessel biofouling have not received the same level of attention. To inform future policy and management decision-making, it is recommended that propagule pressure is better quantified through hull surveys of a variety of vessel types on different routes to Antarctica and at different points in the austral summer season. Simple and cost-effective mitigation measures, such as intentionally moving transiting ships briefly through available sea ice to scour off accessible biofouling communities, may substantially reduce hull-borne propagule pressure to the region. Information on offshore sea ice effects on biofouling may also be of benefit to policymakers with responsibility for the Arctic, where shipping activity is also increasing and marine communities are likely to be at increasing risk of invasion (Miller and Ruiz, 2014; Ware *et al.*, 2014).

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