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Vessel biofouling and bioinvasions in Arctic waters

Submitted by Friends of the Earth International (FOEI)

SUMMARY

Executive summary:	FOEI offers an independent report, set forth in the annex, that provides findings and recommendations concerning vessel coatings and the protection of Arctic waters from bioinvasions
Strategic direction, if applicable:	1, 3 and 7
Output:	Not applicable
Action to be taken:	Paragraph 3
Related documents:	MEPC.207(62); MEPC.1/Circ.792, MEPC.1/Circ.811; MEPC 72/15/1 and MEPC 72/INF.11

Introduction

1 In light of ongoing efforts to address vessel biofouling, including a new work output to review the 2011 Biofouling Guidelines (resolution MEPC.207(62)) and the GloFouling Partnerships project, the sponsor commissioned the following report titled "An Assessment of Using Biofouling Paints to Protect Arctic Waters from Bioinvasions," set out in the annex.

2 The report recommends, inter alia, that, while not a perfect solution, "the use of a durable, epoxy-based coating on the hull, with antifoulant on areas protected from ice scour, combined with a schedule of in-water hull cleaning (especially after long layovers in port before putting to sea) may be a reasonable best management practice for ships that must pass through sea ice."

Action request of the Committee

3 The Committee is invited to note the information provided.

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Annex

An Assessment of Using Antifouling Paints to Protect Arctic Waters from Bioinvasions

A Report for Friends of the Earth US

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Introduction[1]

The goal of this report is to assess the ability of ships' antifouling paints to reduce the risk of biological invasions in Arctic waters. That assessment is made difficult by the fact that the available array of antifouling paints is in a state of flux. A paint type that had dominated the industry for decades—TBT self-polishing co-polymers (TBT-SPCs)—was banned due to environmental concerns. Subsequently a variety of new paint types were developed and brought to market, including both biocide-releasing paints that employ a number of different binder systems with both old and new biocides in various combinations, as well as non-biocidal "fouling release" paints that hamper or weaken the attachment of fouling organisms, along with a few hybrid systems.

Due to the recent development and diversity of the currently available paint types, there is as yet relatively little information on their performance or impacts developed by independent researchers, or released to the public by industry researchers. Even so, some of the biocides that replaced TBT have raised environmental concerns, resulting in regulatory restrictions with the possibility of additional regulations that might force some paints from the market. There is also active ongoing research into new types of antifouling systems, which are at various stages of development.

This report will first discuss various issues regarding biofouling and bioinvasions, including issues specifically relevant to the Arctic; then review the recent history of antifouling paints; and finally discuss how Arctic temperatures might affect the integrity and performance of antifouling paints.

Ships' Biofouling and Bioinvasions

The transport of plants and animals attached to ships' hulls, known as biofouling, is an important vector of bioinvasions.[2] Biofouling also imposes costs on shipping, mainly by slowing vessels and increasing fuel costs. To combat biofouling, a variety of antifouling paints have been developed and applied to ships' hulls, intended either to prevent the initial attachment of organisms or to make it easier to remove them.

In general, considerably more attention has been paid to larger, multicellular fouling organisms than to microscopic, single-celled organisms. Seaweeds, barnacles, tubeworms, hydroids and bryozoans are listed by one author as the most important ship fouling organisms (De la Court & De Vries 1973), although it is recognized that microbial biofilms that develop on ship hulls can significantly increase frictional resistance and fuel consumption (*e.g.* Schultz 2007). Studies of fouling as a vector for bioinvasions have also focused mainly on invertebrates and seaweeds, although fouling, like ballast water, could potentially transport microbes that cause diseases in humans, animals or plants (Cohen 2016).

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[1] The views expressed in this report may not necessarily be those of Friends of the Earth U.S., Friends of the Earth International, or their funders.

[2] This report addresses only external hull fouling. Fouling inside ship's sea chests and internal seawater piping, though potentially an important invasion vector, is not included in this assessment.

Antifouling Economics

Since the research on, development of and use of ships' antifouling paints has been driven primarily by market forces, it's helpful to understand their basis. Hull fouling increases frictional drag which reduces ship speed and hampers maneuverability; fouling can also contribute to corrosion. The effect on speed is the most significant, causing ships to burn more fuel and thereby increasing the cost of voyages. Antifouling paints have been developed and applied in order to avoid these costs.

If a shipowner is an economically rational actor, he or she will pay for a more effective antifouling program (for example, by applying higher performance paints, paying for a more thorough application, or cleaning or repainting the hull more often) if the marginal cost of the additional effort is less than the marginal benefit to be gained, after appropriately discounting future costs and benefits for the expected return on investment. If, on the other hand, the marginal cost is greater than the marginal benefit, he or she will reduce the amount spent on antifouling by opting for a cheaper (and presumably less effective) program. From the shipowner's perspective, the benefit to be compared against the cost of antifouling is the money saved by burning less fuel because the hull is free of fouling organisms. This is what drives the market.

When a shipowner spends money on antifouling, the cost is immediate and known, but the benefit accrues in the future (typically until the next hull repainting, or until the antifoulant is no longer effective), and the size of the benefit is uncertain. The uncertainty stems from several factors, including not being sure how much fouling would accumulate on the hull without the additional antifouling effort, how much less will accumulate as a result of the effort, how much this will reduce fuel consumption, how much the fuel would have cost, and what economic discount factor should be applied to future benefits. In deciding how much to spend on an antifouling program, it's likely that shipowners generally place more weight on the immediate, known costs than on the future, uncertain benefits. If so, less will generally be spent on antifouling than should be spent, given the costs and benefits to shipping.

That, however, is not the whole story. There are costs and benefits that are not felt by the shipping industry and are not captured by the market. Economists call these "externalities." Chief among these are secondary benefits from reducing fuel consumption (fewer air pollutants, smaller carbon footprint); a reduction in the risk of harmful bioinvasions; and, on the cost side, the negative impacts from biocides released into the environment from antifouling paints. These benefits and costs accrue to society generally, rather than to the shipping industry or individual shipping companies specifically. Governments have taken steps to "internalize" the societal costs of antifouling, by banning or limiting the rate of release of some of the more harmful biocides in antifouling paints. This has had the effect of raising the cost of achieving a given level of antifouling performance, which should lead shipowners to opt for a lesser (and cheaper) level of performance.

Governments have been less successful at internalizing the societal benefits of antifouling activities. Government and International Maritime Organization (IMO) initiatives in this area mainly consist of voluntary guidelines[3] or vague, unenforceable "requirements" that in reality function merely as recommendations, and which in some cases simply reflect practices that are already common in the industry (California SLC 2013; Hagan *et al.* 2014).[4] Unless mandatory, enforced regulations or market forces drive shipowners to adopt more aggressive antifouling programs, it is unlikely that many will. Indeed, market forces would punish any shipowner that, without being required by regulations to do so, spent extra money on antifouling efforts in order to prevent bioinvasions or otherwise reduce environmental impacts.

One other point about antifouling efforts being driven by relative costs and benefits is that these factors differ among ship types, leading different classes of vessels to typically adopt different levels of antifouling effort. Faster vessels that have short layovers between voyages gain substantial savings in fuel costs from effective antifouling treatment; these types of vessels, including high-speed ferries, cruise ships and ships in the liner trade,[5] more often opt for high performance antifoulants. In contrast, vessels that travel at slower speeds and remain for longer periods in a port or at a work site between voyages—such as barges, certain specialized working vessels including semi-submersible drilling platforms, and charter vessels[6]—gain smaller fuel cost savings from a given level of fouling prevention, making lower-performing but cheaper antifoulants more cost-effective (J.A. Lewis, pers. comm. 7/12/2018).

Biofouling and the Arctic

Arctic Temperatures

This paper follows Cohen (2017) in considering Arctic marine waters to comprise two subregions:

- *Arctic Core waters* consist of waters north of Eurasia, North America and Greenland, extending south in the Atlantic to Baffin Bay, Davis Strait and the West Greenland Shelf, the Greenland Sea, north of the Iceland Shelf, and the northern and eastern Barents Sea east of the White Sea. These are included within the boundaries of the Arctic as defined by numerous researchers and multi-national programs, including Ekman's (1953) Arctic Region, the Arctic Monitoring and Assessment Program

[3] The IMO adopted voluntary guidelines for ships in 2011 and for recreational vessels in 2012 (IMO 2011, 2012). It subsequently issued guidance for evaluating the ship guidelines (IMO 2013), and in April 2018 agreed to review the ship guidelines based on the principles outlined in the guidance document.
[4] Additionally, there is a lack of agreement about what those recommendations should include. For example, some authorities and jurisdictions encourage in-water hull cleaning, while others discourage or ban it because of concerns about releasing larger quantities of fouling organisms and antifouling biocides into the environment (Lewis & Coutts 2010; Hagan *et al.* 2014).
[5] The liner trade refers to cargo vessels with regularly scheduled runs on fixed routes, which typically include containerships and roll-on/roll-off ships.
[6] Charter vessels, which, depending on market conditions, may be subject to long layovers while waiting for a charter, typically include bulkers and oil tankers.

region (AMAP 1998); OSPAR's (2000) Arctic Maritime Region, Spalding *et al.*'s (2007) Arctic Realm, the Arctic's Large Marine Ecosystems as defined by UNEP (Sherman & Hempel 2009) and PAME (2013), the Marine Study Units of the World Wildlife Fund's RACER Project (Christie & Sommerkorn 2012); and the region covered by the Arctic Register of Marine Species (Sirenko *et al.* 2018).

- *Subarctic waters* consist of certain areas marginal to the Arctic Core region, each of which were included in one or more but not all of the above-referenced definitions of the Arctic's boundaries. In the Pacific Ocean these include waters of the Bering Sea, coastal waters extending to the tip of the Kamchatka Peninsula, the Okhotsk Sea, the northern Kurile Islands, and the southern Alaska coast from the Aleutian Islands to near Yakutat Bay at 60° N latitude. In the Atlantic Ocean region these include the western Labrador Sea to northern Newfoundland, the East Greenland Shelf, the Iceland Shelf, the Faroe Plateau, Norwegian coastal waters north of 62° N latitude, the coastal waters of the Kola Peninsula, and the White Sea.

Prior to recent climate shifts, Arctic Core waters had average winter sea surface temperatures between around –2°C (the freezing point of seawater[7]) and 0°C, and average summer sea surface temperatures below around 5°C. In subarctic waters, average winter temperatures were mainly below 2°C but were as high as 7-8° in some locations; average summer temperatures were mostly below 10°C but as high as 13°C in some places (Sverdrup *et al.* 1942; Ekman 1953).

Data since 1982 for the Arctic Core shows a substantial rise in summer sea surface temperatures in some areas and less elsewhere: +2.5°C in the Chukchi Sea and +2.1°C in East Baffin Bay, but only +0.3°C in the Laptev and East Siberian seas, +0.1°C in the Kara Sea, and no change in the Barents Sea (part of which is classified here as Subarctic) (Timmermans & Proshutinsky 2014, 2015; Timmermans 2016; Timmermans *et al.* 2017). While summer surface temperatures across most of the Arctic Core remain below 6°C, in some years they rise above 6°C in eastern Baffin Bay and above 10°C in southern Barents Sea and southeastern Chukchi Sea (Fig. 1).

In Arctic marine areas that are iced over in the winter, average summer air temperatures tend to be around 0 to 2°C, and average winter air temperatures range from around –15 to –35°C with minimums around –50°C. In areas that are ice-free year-round, average summer air temperatures are usually less than 10°C and average winter air temperatures are around –2° to 0°C (Fig. 2).

[7] The precise freezing point depends on the salinity of the water. Water with a salinity of 35 psu freezes at -1.8°C.

Fig. 1. Mean August sea surface temperatures, mean August sea ice extent, and 10°C SST isotherm (gray contour line) in the Arctic, 2015-2017. From Timmermans & Proshutinsky 2015; Timmermans 2016; and Timmermans *et al.* 2017.

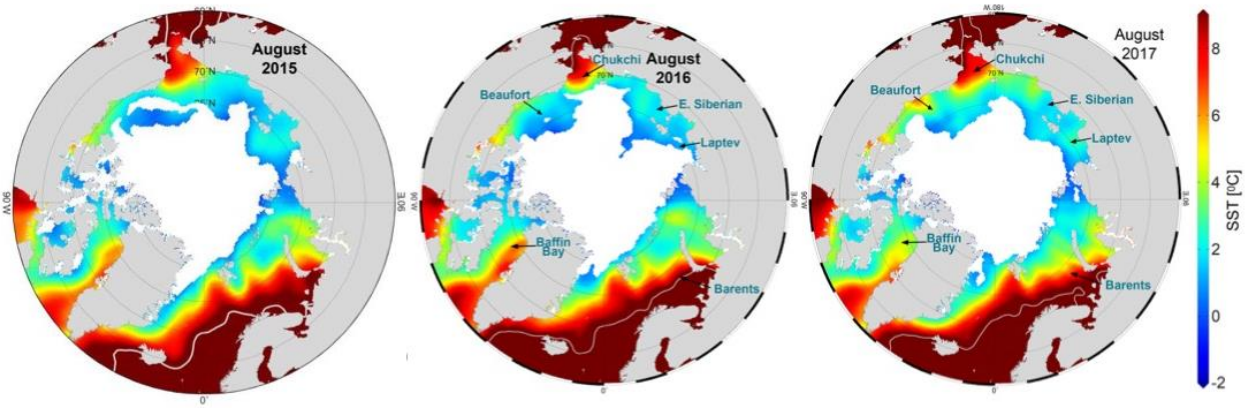
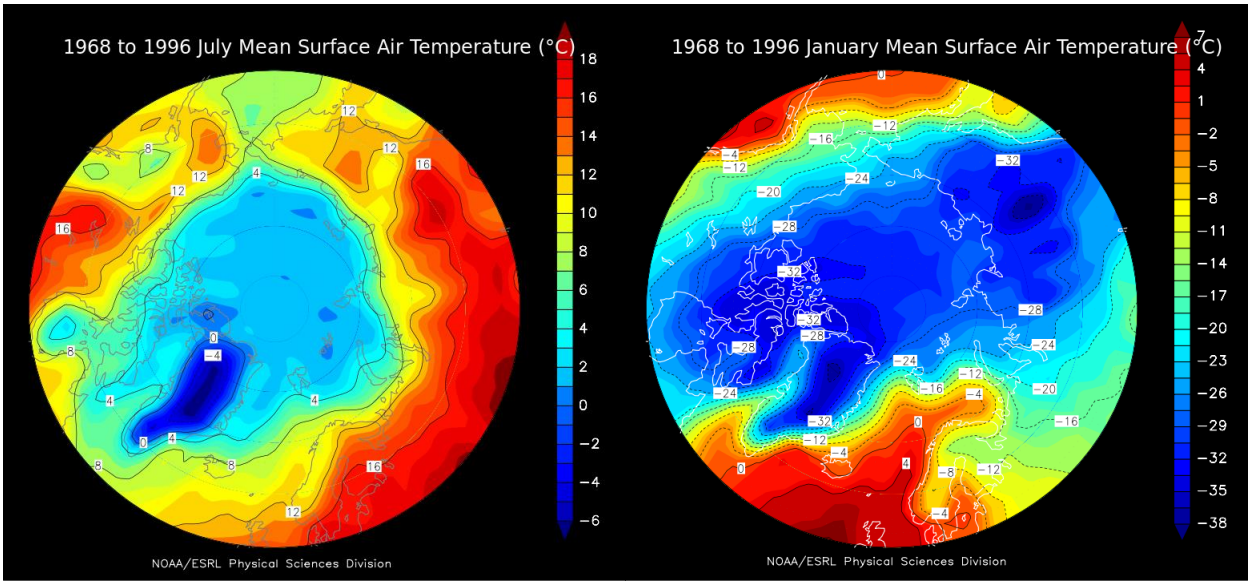


Fig. 2. Summer and winter air temperatures in the Arctic. From Earth Sciences Research Laboratory, National Oceanic and Atmospheric Administration.



Effect of Sea Ice

Passage through sea ice most likely reduces the immediate risk of introducing non-native species into the Arctic by scraping biofouling organisms from ships' hulls (Lewis *et al.* 2003, 2004; Lee & Chown 2009; Paloczanska & Butler 2010; Chan *et al.* 2012, 2015; Hughes & Ashton 2016), although some authors have warned that this could also increase risk by releasing those organisms into the water (Chan *et al.* 2012). In addition, damage to a ship's antifouling coating from ice abrasion can increase hull fouling and the risk of transporting non-native species on subsequent voyages (Lewis *et al.* 2003,

2004; SCAR 2007; Lee & Chown 2009; Hughes & Ashton 2016), as well as release larger amounts of antifouling biocides into the environment (Negri *et al.* 2004; Lewis *et al.* 2004; Negri & Marshall 2009).

There are a few field studies on the effect of sea ice on fouling and antifouling in the Antarctic but none in the Arctic. Lewis *et al.* (2004) compared the hull fouling on two research vessels before and after voyages to Southern Ocean research stations. One ship left Tasmania with extensive, biologically diverse hull fouling and returned with no detectable fouling after a voyage to the Antarctic Peninsula at 66° S that involved passing through first year sea ice that was up to 1 m deep. The other ship left Freemantle in Western Australia with more modest fouling and returned with the extent and diversity of fouling essentially unchanged after a voyage through ice-free seas to the sub-Antarctic Heard Island at 53° S. Though the first ship's voyage was longer and to a higher latitude, the authors concluded that it was passage through sea ice that was responsible for the difference in fouling survival, as other environmental factors, including the water temperatures encountered, were not greatly different.

Lee and Chown (2009) studied changes in the hull fouling on a supply ship over a two-year period as it traveled between Cape Town, South Africa and research stations on the Antarctic continent at 72° S and on two sub-Antarctic islands at 40° and 47° S. During the first 5 months of the study, while the ship still had an intact coat of antifouling paint, the only fouling observed consisted of biofilms and fine algae. On the first of two voyages through sea ice to Antarctica approximately 30% of the antifouling coating was lost. On return to Cape Town, the paint-free areas of the hull were rapidly colonized by seaweeds and macro-invertebrates, including barnacles, tunicates and hydroids. A second passage through sea ice to Antarctica the following summer again removed all fouling, along with additional antifouling paint.[8] Voyages to the sub-Antarctic islands, which did not involve passing through sea ice, reduced the extent of hull fouling but left a substantial portion intact.

Hughes and Ashton (2016) surveyed the hull fouling on a research vessel on its arrival at Antarctica, after passing through sea ice, at the start of four summer seasons. The ship had been dry-docked and painted with an antifouling paint 17 months before one visit and 4-5 months before the others. There was no fouling on surfaces exposed to ice scour, but small niche areas that were protected from the ice harbored microbial/algal biofilms and, on two of the visits, a few live barnacles. Much of the antifouling paint had also been stripped off the hull, especially around the waterline.

Biofouling and Invasions in the Arctic

To date, few non-native species have become established in Arctic waters (Cohen 2016). This is probably due to the limited transport of non-native species into Arctic

[8] The authors were not able to conduct before-and-after surveys of the paint condition because of the extensive fouling on the hull at the start of the second voyage, but thought it "likely that an equivalent amount of antifouling coating was removed" as in the first voyage.

waters, in combination with the Arctic's challenging physical conditions which may make establishment difficult.

The Arctic, however, is changing. Warmer waters and retreating sea ice invite economic activities—including cargo transport along new sea routes; mineral, oil and gas extraction; tourism; and the expansion of fisheries—that will greatly increase opportunities to transport non-native species into and across Arctic waters. These changing environmental conditions will also stress populations of native species, potentially increasing their vulnerability to invasion, while simultaneously increasing the ability of non-native species from lower latitudes to become established.

It is helpful to divide the marine world into four areas from which Arctic waters could, in concept at least, receive non-native fouling organisms. First, fouling organisms could be transported from Arctic waters into other Arctic waters where they are not native. Second, fouling organisms could be transported to the Arctic from northern temperate, especially cold temperate, waters. As Arctic waters warm, they will become increasingly hospitable to invaders from the temperate zone. Third, fouling organisms could be transported from tropical/subtropical waters in the Northern or Southern Hemisphere, but such organisms are physiologically unlikely to be capable of establishing in the Arctic, even with projected warming. Thus, the prospect for successful Arctic invasions by tropical or subtropical fouling organisms seems dim. Finally, fouling organisms could be carried from Southern Hemisphere temperate or polar regions to the Arctic. At least some organisms from these regions would likely be able to establish themselves in the Arctic, if enough healthy individuals were introduced. However, because of the necessity of passage through lower latitudes in direct contact with warm tropical surface waters, fouling organisms from cold-enough regions of the Southern Hemisphere would be unlikely to make it alive to the Arctic.[9] Thus, for fouling organisms, we need only consider Arctic-to-Arctic and Northern Temperate-to-Arctic invasions as significant risks.

It is sometimes suggested that there is no biofouling in the Arctic,[10] which would eliminate any concern about Arctic-to-Arctic fouling invasions. Though the fouling biota is apparently less diverse in the Arctic than in warmer regions (Witman *et al.* 2004; Canning-Clode & Wahl 2010), there are Arctic organisms that will attach to floating objects including ships. WHOI (1952) lists two barnacles, a clam, two tunicates and two seaweeds as among Arctic biofoulers. Meyer *et al.* (2017) reported on recruitment to suspended fouling panels in two fjords at Svalbard both in summer, when water temperatures rose to 5-6°C, and at a lesser but still significant rate in winter, with

[9] Tavares & De Melo (2004) identified two crabs collected on the Antarctic Peninsula 14 years earlier as a North Atlantic/Arctic species *Hyas araneus*. The crabs had been in the collection of a Brazilian museum, and Thatje (2005), expressing doubt about such an introduction, suggested that the specimens might have been mislabeled and had actually been collected in the Northern Hemisphere. Since then, the crab has not been observed south of the North Atlantic, and researchers no longer consider it to be introduced to the Antarctic (Griffiths *et al.* 2013; Hughes & Ashton 2016). Thus, we have no good record of any marine species introduced across the equator into a polar region.

[10] *E.g.*, "The navigation season in the high Arctic is only 2-3 months 'short' and with little marine life in the cold water anti-fouling paint is never needed" (Johansson 2013).

temperatures of 0 to -2°C.[11] Common foulers included seaweeds, barnacles, a spirorbid tubeworm, a clam and numerous species of bryozoans. Matsson *et al.* (2018) reported that a laminarian seaweed grown on lines in Norway yielded the largest biomass at a site above the Arctic Circle. This same seaweed was reported as a dominant fouler of suspended panels in the coldest waters at Svalbard (Meyer *et al.* 2017). As shown in Fig. 3, Arctic fouling can be substantial.

Fig. 3. Examples of biofouling on buoys in Arctic waters. A: Bering Strait in 2010; B-D: northwestern Bering Sea in 2012. Photographs by Aleksey Ostrovskiy, RUSALCA expeditions, https://www.pmel.noaa.gov/rusalca/gallery.



[11] Dayton (1989) noted that in the Antarctic even benthic species with demersal larvae can sometimes colonize floating objects by rafting upward with anchor ice, and the same mechanism may operate in Arctic waters.

Out of the previously reported 37 non-native species in Arctic marine waters (Cohen 2016), 18 may have been introduced in hull fouling[12] based on their history, distribution and life history, and on records of some of them in ship or buoy fouling (Table 1). Each of these could potentially be introduced to new sites in the Arctic via hull fouling, and each appears to have arrived in the Arctic from previous locations in Northern Hemisphere temperate waters.[13] They thus provide evidence of the ability of fouling species from such waters to become established in the Arctic,[14] which in some cases occurred even before there was any detectable warming of Arctic waters from anthropogenic climate change.

Table 1. Species possibly introduced to the Arctic in hull fouling. The Arctic Realm, LMEs and regions are defied in Spalding *et al.* 2007, Sherman & Hempel 2009, PAME 2013 and AMAP 1998.

Higher Taxon	Species	Above the Arctic Circle	Arctic Realm	PAME/UNEP Artic LMEs	AMAP Region
Rhodophyta	*Bonnemaisonia hamifera*	X		X	X
Rhodophyta	*Caulacanthus ustulatus*				X
Rhodophyta	*Ceramium sinicola*				X
Rhodophyta	*Chroodactylon ornatum*				X
Rhodophyta	*Dasysiphonia japonica*			X	X
Rhodophyta	*Dumontia contorta*	X	X	X	X
Chlorophyta	*Codium fragile tomentosoides*	X		X	X
Phaeophyta	*Colpomenia peregrina*			X	X
Phaeophyta	*Fucus evanescens*	X		X	X
Phaeophyta	*Fucus serratus*			X	X
Phaeophyta	*Microspongium globosum*				X
Cirripedia	*Amphibalanus improvisus*			X	X
Amphipoda	*Caprella mutica*	X	X	X	X
Decapoda	*Cancer irroratus*			X	X
Bryozoa	*Schizoporella japonica*				X
Tunicata	*Botrylloides violaceus*				X
Tunicata	*Ciona intestinalis*			X	X
Tunicata	*Molgula citrina*				X

[12] Some of these might have been introduced by other vectors, such as ballast water.

[13] The brown seaweed *Fucus serratus* appears to have followed this pattern of introduction into the Arctic from temperate waters (genetic analysis indicates it was probably carried from southeastern Norway to Iceland in the 18th or 19th Century) followed by secondary introduction to other Arctic sites (from Iceland to the Faeroe Islands in the late 20th Century; Coyer *et al.* 2006; Thorarinsdottir *et al.* 2014).

[14] The appearance of the mussel *Mytilus edulis* in Svalbard (Berge *et al*. 2005)—which may have resulted from larvae carried north in ocean currents, as the authors argue, or possibly from transport in ballast water or hull fouling—is another case of a temperate zone species successfully establishing in the Arctic. Also, the sole confirmed marine invasion in the Antarctic is a common hull-fouling species, the green seaweed *Ulva intestinalis* (Clayton *et al.* 1997; Hughes & Ashton 2016).

A few studies have directly examined the transport of fouling species from Northern temperate waters into the Arctic:

- Using a remotely operated vehicle with a mounted video camera, Ware *et al.* (2012) inspected the hulls of 12 vessels that arrived at the port of Longyearbyen in Svalbard at 78° N, and found biofouling on ten of them. One recreational vessel was heavily fouled, having laid up over the winter in a mainland Norwegian port. Overall, fouling was associated with older paint, slower ships and longer layovers.
- Chan *et al.* (2015) sampled the hull fouling on 13 ships—nine bulk carriers, two general cargo ships, one roll-on/roll-off vessel and one supply tug—arriving in Churchill on Hudson's Bay at 59° N. The ships arrived in the summer, when water temperatures ranged up to 8°C. They typically sailed at 7-11 knots, and it had been 4 to 23 months since their last dry-docking and antifouling application. Two of the previous ports of call were in the Canadian Arctic, two were in the northwest Atlantic, seven were in Europe, and one was in South America (one could not be determined from the map provided). Some ships had extensive fouling, covering up to 10-28% of the wetted hull surface. The authors found a total of 86 distinct invertebrate taxa (excluding taxa that were also found in samples of port water taken at the same time), and identified 34 of them. Sixteen of these had been reported in the Canadian Arctic, three had been reported from other parts of the Arctic but not in Canada (and thus represented potential Arctic-to-Arctic introductions of non-native species) and 15 had been reported from Northern Hemisphere temperate waters but not from the Arctic (potential Northern Temperate-to-Arctic introductions).
- Chan *et al.* (2016) sampled hull fouling on four naval ships after voyages from Halifax (at 45° N, with an annual mean surface water temperature of 8.5°C) to Churchill (59° N, with 4.3°C) or one of three northern Canadian Arctic ports (64-75° N, with 0°C). The ships generally travelled at 10-12 knots; a copper-based antifouling paint had been applied to their hulls 2-4 years prior to the voyages. Fifty-eight distinct taxa were collected from the ships' hulls on arrival at the Arctic ports and 42 of these were identified to genus or species. Of those, six had not previously been reported in the Canadian Arctic, and were thus potential Northern Temperate-to-Arctic introductions.

These studies of fouling transport, as well as the known fouling species from northern temperate regions that have become established in the Arctic, make it clear that there is a significant risk of invasions in the Arctic resulting from hull fouling, both Arctic-to-Arctic and Northern Temperate-to-Arctic. With further warming of the Arctic seas, the risk of the latter can only increase.

Antifouling Paints

Biofouling on ships causes a variety of problems (Yebra *et al.* 2004; Chambers *et al.* 2006):

- Fouling adds roughness to the hull surface which increases surface friction and hydrodynamic drag, thereby impairing vessel maneuverability and either reducing vessel speed or requiring a higher rate of fuel consumption to compensate. Reducing speed and/or increasing fuel consumption can impose large costs on shipping companies. Increased fuel consumption also increases a vessel's air emissions.
- Fouling also increases the need for hull cleaning, which may require more frequent dry-docking, and can hasten the deterioration of hull paints meant to reduce corrosion and surface friction. These also impose costs on shipping companies.
- Fouling organisms are transported to new regions where they can become established and cause environmental, economic and public health problems.

The process of biofouling has been described as a sequence starting within minutes of submergence as electrostatic and Van der Waal's forces cause organic molecules to adhere to the wetted surface; pioneering bacteria and other micro-organisms then attach to the surface within hours to days; these organisms secrete polymers that contribute to the development of a biofilm that anchors, envelopes and protects these and other micro-organisms (including sulfate reducing bacteria, which can initiate microbially induced corrosion of the hull). Biofilm formation is followed by the settlement of micro- and macro-invertebrates and algae over a period of weeks to months (Lewis 1998; Nandakumar & Yano 2003; Yebra *et al.* 2004; Chambers *et al.* 2006; Almeida *et al.* 2007).

A variety of anti-fouling paints have been developed for ships in order to reduce fouling and thereby improve hydrodynamic performance and reap the benefits of either a faster ship or reduced fuel consumption. On most ships in active service the densest hull fouling is not on the large, smooth expanse of the hull but in topographically complex and sheltered niche areas, including on and around the propeller, rudder, bilge keels, bow thrusters, anodes and intake gratings, and also in places where antifouling paint hasn't been applied such as the strips where support blocks hold a ship in drydock during paint application (Cordell *et al.* 2009; Sylvester *et al.* 2011; Chan *et al.* 2015). Preventing or removing fouling on these relatively small and sometimes difficult to access areas does little to improve ship performance compared to keeping the main hull surface generally free of fouling, but may be important in reducing the risk of bioinvasions (Hagan *et al.* 2014).

Ship speed, the age of the anti-fouling paint, time since the last hull cleaning, and the time spent in port can all affect the amount of fouling. There is usually little fouling except in niche areas on ships travelling faster than 15 knots, but significant fouling on all parts of the hull on ships travelling slower than 10 knots (Cordell *et al.* 2009).

Most biofouling settles when a ship is in port or is moving at low speed (Almeida *et al.* 2007). Ships typically have their hulls cleaned and repainted every five years, during a scheduled drydocking (Cordell *et al.* 2009).

Antifouling paints, primarily using copper compounds, mercury oxide or arsenic, had been used on ships from the 1840s onward. These evolved into two types, based on their binder systems. One type, known as insoluble matrix, contact leaching, continuous contact or free-association paint, has a vinyl, epoxy, acrylic or chlorinated rubber polymer matrix. This matrix is mechanically strong and doesn't erode or "polish" in water, and has dispersed within it soluble pigments and biocides. Seawater diffuses into the paint through interconnected pores formed by dissolution of the soluble components. As these channels lengthen through a thickening leached layer and become increasingly clogged, an initially high biocide release rate drops exponentially, typically limiting the paint's effective life to 1-2 years (Champ & Seligman 1996; Thomas *et al.* 1999; Yebra *et al.* 2004; Almeida *et al.* 2007; Finnie & Williams 2010).

The other type of paint, known as soluble matrix, controlled depletion, ablative or erodible paint, incorporates a matrix that dissolves in seawater, with rosin as a main ingredient. As in insoluble matrix paints, biocide particles are mixed into the matrix, but instead of dissolving out through channels they are released as thin layers of the paint are eroded away. This requires some water flow past the paint surface in order to work effectively, so this type of paint provides minimal biocidal effect when the ship is stationary and most rapidly accumulating fouling. These paints typically last 2-3 years, during which time the rate of biocide release declines exponentially (Champ & Seligman 1996; Thomas *et al.* 1999; Yerba *et al.* 2004; Almeida *et al.* 2007; Finnie & Williams 2010).

Starting in the 1970s, paints that incorporated tributyltin (TBT) as the primary biocide in a "self-polishing copolymer" became the dominant type of antifouling paint on commercial vessels. Polymers are molecules that consist of a chain of repeating units, called monomers; a copolymer is a polymer constructed with two different monomers. In TBT-SPC paints the matrix was usually a copolymer of methyl methacrylate and TBT methacrylate. Additional "booster" biocides, usually cuprous oxide, were dispersed in the matrix. In seawater, the TBT in the top few nanometers of the paint is sliced (hydrolyzed) from the polymer backbone and released into the water. This allows water to penetrate a short distance into the paint and leach out the cuprous oxide. Also, the loss of TBT leaves the copolymer brittle and more easily worn away or "polished." After an initial brief period with a high rate of biocide release, a thin leached layer is formed that migrates down through the paint, eroding at its upper surface (the surface in contact with water). This produces a roughly constant rate of biocide release, which continues over paint lifetimes of 5 years or more. In addition, the paint tends to erode more rapidly at rough spots on the paint surface, thereby smoothing them out (hence "self-polishing"), and further reducing frictional resistance (Lewis, 1998; Thomas *et al.* 1999; Kiil *et al.* 2002a; Yerba *et al.* 2004; Chambers *et al.* 2006; Almeida *et al.* 2007; Dafforn *et al.* 2011; Lindgren *et al.* 2016).

By manipulating the polymer chemistry, manufacturers could adjust the rate of surface erosion and biocide release. This allowed the development of specialized paints: slow polishing paints for high speed vessels, and fast polishing paints for slow vessels with long stationary periods (Yerba *et al.* 2004; Almeida *et al.* 2007). With their long lifetimes, steady biocide release rates, and wide-spectrum biocidal activity, TBT-SPC paints quickly gained a large share of the market, eventually being used on around 70% of the world's ocean-going ships (Kiil *et al.* 2002b,c; Lindgren *et al.* 2016).

However, in the early 1980s researchers determined that oyster deformities reported by French oyster farmers were produced by TBT contamination, primarily coming from antifouling paints. Sex changes and deformities in snails were also traced to TBT, and TBT was found to bioaccumulate in fish, birds and marine mammals (Chambers *et al.* 2006). France was the first country to adopt a ban on the use of TBT in antifouling paints, which applied to vessels under 25 meters in length. Other counties and the European Union followed with additional bans or restrictions, and in 2001 the IMO adopted a Convention banning the application of TBT to any vessel after 2002, and banning its presence as an active paint on any vessel after 2007[15] (IMO 2001; Almeida *et al.* 2007; Dafforn *et al.* 2011).

Paint manufacturers began searching for replacements for TBT paints, but found it difficult to replicate the characteristics that made TBT-SPCs successful (Yebra *et al.* 2005; Pei & Ye 2015). It wasn't merely the broad-spectrum biocidal qualities of TBT that made it so useful, but also its role as a component of the copolymer in regulating the polishing rate of the paint. As one researcher described the problem (Yebra *et al.* 2006):

> The main difficulty in developing efficient antifouling products is that the coupling of the main paint processes is so marked that typically only very few formulations among a large number of possibilities result in adequate paint polishing and biocide leaching simultaneously. The substitution of one major paint component may cause a dramatic misbalance in the performance, which often takes years of research and development to solve.

But gradually the paints have improved. Many of these are copper, zinc or silyl acrylate copolymers that have self-polishing qualities comparable to those of the TBT-SPCs (Finnie & Williams 2010). Copper is the most widely-used primary biocide. Because it is not very effective against seaweeds and certain other organisms, a variety of booster biocides are incorporated into paints along with it, including Irgarol, diuron, chlorothalonil, dichloro-octyl-isothiazolin (DCOIT, Sea Nine 211®) and zinc and copper pyrithione (Zinc and Copper Omadine®) (Yebra *et al.* 2004; Dafforn *et al.* 2011).

As more has been learned about the impacts of these biocides, countries have begun adopting restrictions on them. Denmark and Canada have enacted limits on copper release rates from antifouling paints used on recreational vessels. Copper input limits have been set for San Diego Bay in southern California that will require changes in the

[15] Because of the time needed for enough countries to ratify the Convention, it did not go into effect until September 2008. It's possible that TBT is still used on domestic vessels in non-signatory countries (Dafforn *et al.* 2011).

paints used there. Sweden has banned all biocidal antifouling paints on recreational vessels on its Baltic coast (Pereira & Ankjaergaard 2009; Dafforn *et al.* 2011). Paints using Irgarol are banned in Denmark and Australia and restricted to vessels over 25 meters in length in the United Kingdom. Paints using diuron are banned in Denmark, The Netherlands and the United Kingdom. Paints using chlorothalonil are banned in the United Kingdom (Chambers *et al.* 2006; Dafforn *et al.* 2011). It seems likely that there will be more restrictions in the future, which will continue to cause shifts in the array of available antifouling paints.

Paints with low-friction, ultra-smooth surfaces that prevent strong attachment by fouling organisms, known as fouling release coatings, provide an alternative to biocide-based paints. These are usually made from silicones or fluoropolymers (Yebra *et al.* 2004). Since organisms cannot adhere strongly to these surfaces, they are dislodged when the ship speed rises above a critical velocity. The paints do not prevent biofouling while the ship is stationary, and in general are effective solutions only for high speed vessels that travel at greater than 20 knots, or that travel at greater than 15 knots and are idle only for short periods (Chambers *et al.* 2006; Almeida *et al.* 2007; Dafforn *et al.* 2011). These may include high-speed ferries, container ships, gas carriers and cruise ships (Dafforn *et al.* 2011). The paints generally show poor resistance to abrasion, but the thinner fluoropolymer paints may be more resistant then the silicone-based paints (Yebra *et al.* 2004; Almeida *et al.* 2007).

Many other approaches to antifouling coatings are being explored by researchers, including biocides made from natural products, the use of enzymes as biocides, and coatings with surface microtopographies that prevent adhesion by organisms. It's unclear whether these will be developed into marketable products, or how long that will take.

Performance of Antifouling Paints in Arctic Conditions

Data Limitations

A previous assessment of the performance of ballast water treatment systems relative to Arctic bioinvasions was based on data from tests of those treatment systems conducted with a common set of protocols (Cohen 2017). No similar series of tests exists for ship antifouling paints, making an assessment of their relative or absolute effectiveness more challenging. In addition, although water temperature clearly affects the chemical and physical processes by which antifouling paints work, there has been little investigation of the impact of temperature on antifouling efficacy.

Yebra *et al.* (2004) described the overall situation as follows:

> Little attention has been paid to the influence of the different sea water parameters on the performance of chemically active A/F [antifouling] paints. It has recently been shown that chemical reactions and diffusion phenomena are key mechanisms in the performance of biocide-based A/F paints, and that these can be markedly affected by sea water conditions...Sea water has to penetrate into the paint, dissolve such biocides and diffuse out into the bulk phase again...The influence of temperature is...significant as it affects the rate of all chemical reactions, dissolution rates and transport processes associated with the activity of chemically active A/F paints...It is most likely that sea water...temperature will also play a significant role in the reactions associated with the current tin-free biocide-based paints...Despite these facts, most studies dealing with the development of new chemically active A/F binders or paints lack studies on the behaviour of such systems in waters under conditions different from the “standard” or “average” ones. This could eventually lead to biocide-based paints performing excellently under certain conditions but failing in waters with different characteristics.

Fourteen years later, an extensive literature review and correspondence with a number of antifouling researchers yielded only a single study with any data on the performance of antifouling paints below 10°C, and very few that compared performance across any set of temperatures. It's possible that paint manufacturers have tested their products across a broad range of temperatures and thereby acquired substantial data on the relationship between temperature and performance, but if so those data have not been made available to the public either through the peer-reviewed scientific literature or other means.

Temperature and Damage to Antifouling Paints

The technical data sheets for several biocidal antifouling paints (advertised primarily for application on boats rather than cargo ships) include general statements that extreme temperatures could harm the paints. A California Sea Grant pamphlet on hull paints for boats provided a similar warning (McCoy & Johnson 1995). Yebra and Weinell (2009), discussing antifouling paints for cargo ships, reported that changing temperatures stress antifouling paints and can affect their durability. Inquiries to paint manufacturers and antifouling researchers yielded no further information about possible damage to antifouling paints from extreme temperatures or changing temperatures.

Water temperatures may run as low as around -2°C throughout the year in the Arctic Core region, and down to 5°C in the summer and below 0° in the winter in some Subarctic waters. Average air temperatures drop below 10°C in the summer and down to -2°C in the winter in Arctic waters that are ice-free all year. Where ocean waters are ice-covered in the winter, air temperatures get down to -2°C in the summer and -35°C (rarely -50°C) in the winter. Parts of a ship's hull that are in contact with the ocean when a ship is fully loaded may be exposed to the air when the ship is in ballast, is in rough seas, or is transferring cargo.

Temperature and Antifouling Performance

The literature review and inquiries yielded no studies or data on how any direct measure of antifouling performance changes with temperature or latitude, for either biocidal paints or fouling release paints.

Regarding biocidal paints, I found a small number of studies that provide limited data and/or models showing the relationship between water temperature and polishing rates (Kiil *et al.* 2001, 2002b) or between water temperature and biocide release rates (Ferry & Carritt 1946 (this study was also reported in WHOI 1952); Van Londen 1963; Marson 1969; Shatzberg 1990, 1996; Kiil *et al.* 2002b; Yebra *et al.* 2005; Radenovic *et al.* 2014; Sørensen *et al.* undated). The earlier studies deal with contact leaching paints, and the more recent ones deal mostly with self-polishing co-polymers. In each case these studies show lower polishing rates or lower biocide release rates at lower temperatures. For any antifouling paint, a lower polishing rate will produce a lower biocide release rate, with the precise relationship depending on the paint.

In some of the studies on biocide release rates, the data fit an Arrhenius equation model (*i.e.* the log of the biocide release rate changes proportionally with the inverse of the temperature in Kelvin degrees); in others the data fit a linear equation (*i.e.* the biocide release rate changes proportionally with temperature); and in the remaining studies only two data points are published so there is no basis for fitting a model.

Figures 4 and 5, based on the data from the studies cited above, show the estimated biocide release rates that would occur at lower temperatures as a percentage of the release rate at 20° or 30°C. The estimates from data that fit either an Arrhenius or a linear model are based on those models, and are shown as dotted or dashed lines, respectively. The estimates from studies that published only two data points are based on an Arrhenius model fitted to those points, and are shown as solid lines (a linear model fitted to the points would yield lower estimates, *i.e.* greater reductions in biocide release rates with decreasing temperatures). Only one data set appears to be for a current, commercially available paint (Radenovic *et al.* 2014; Sørensen *et al.* undated). Roughly half of these estimates show biocide release rates at 10°C that are less than half of the rate at 20°C and less than one-fourth of the rate at 30°C. Unless the need for biocide similarly drops with temperature—a question taken up below—these data suggest that paints designed for warmer waters will not perform as well in colder waters.

Fig. 4. Estimated biocide release rates as a percentage of the release rate at 20°C. Dashed line: linear equation fit to the data; dotted line: Arrhenius equation fit to the data; solid line: Arrhenius equation fit to 2 data points.

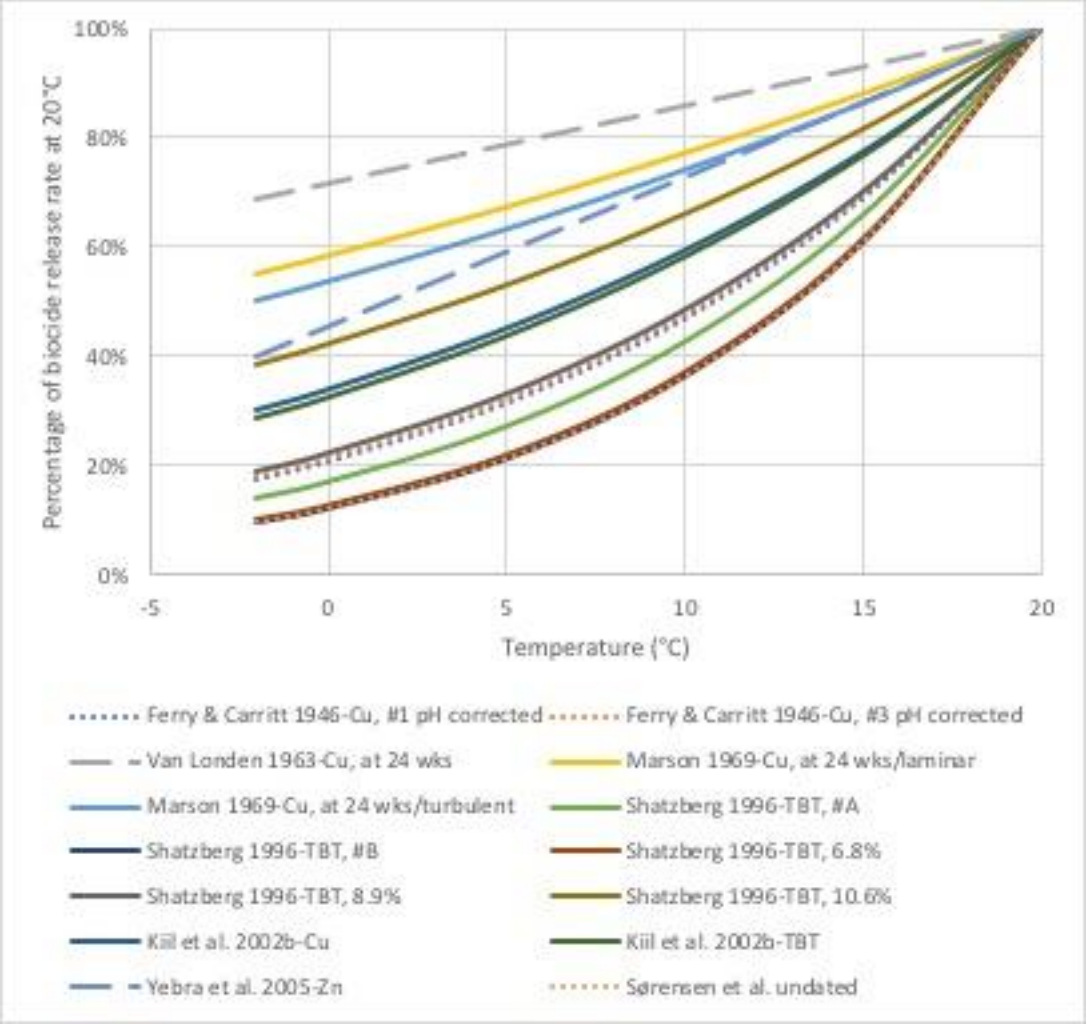
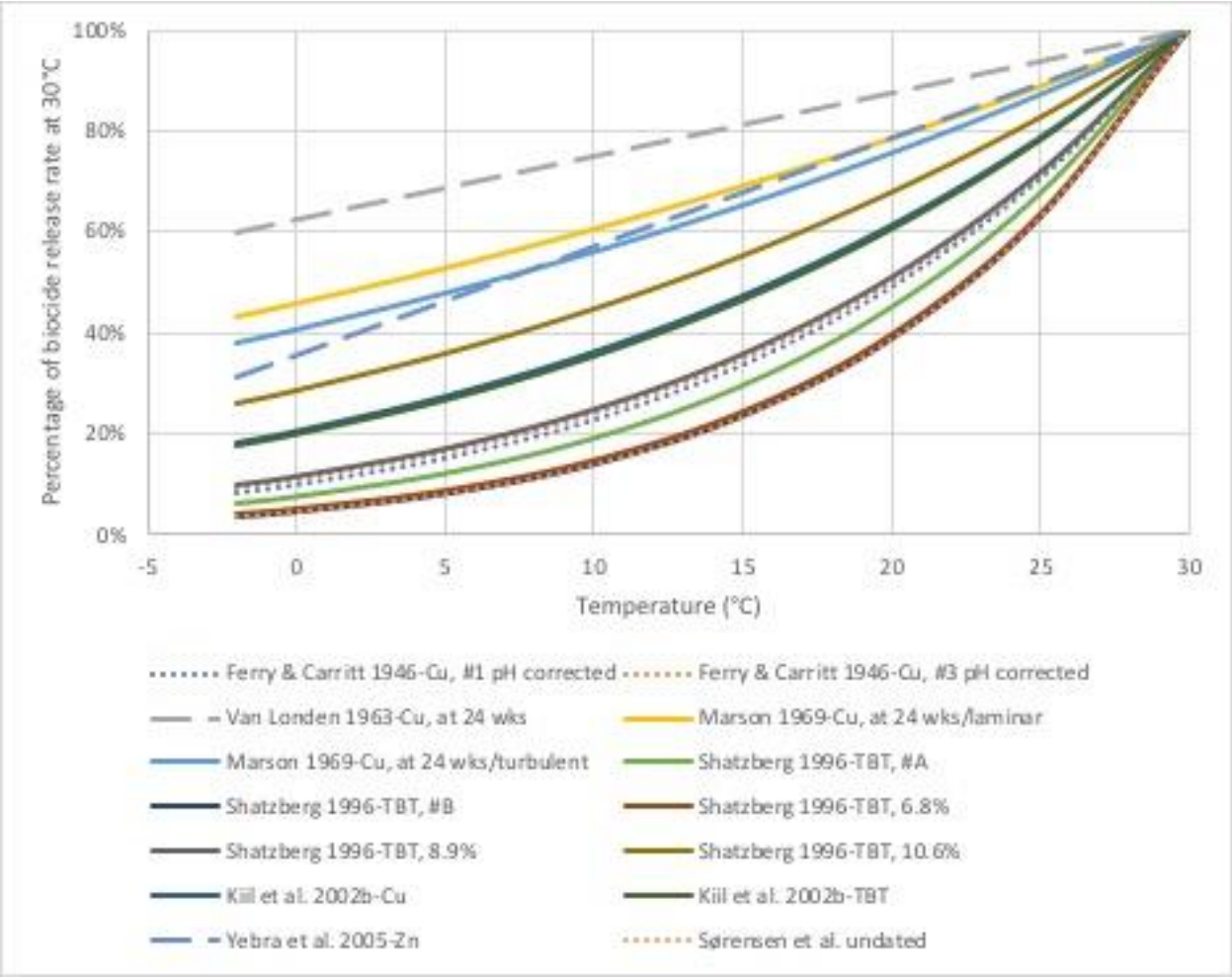


Fig. 5. Estimated biocide release rates as a percentage of the release rate at 30°C. Dashed, dotted and solid lines as in Fig. 4.



In discussing biofouling and antifouling, many authors assert that the rate or severity of biofouling is greatest in the tropics with high water temperatures and is lower at higher latitudes and lower water temperatures, implicitly suggesting that more aggressive antifouling systems are needed in the tropics (*e.g.* WHOI 1952, Yebra *et al.* 2004, Davidson *et al.* 2006, De Nys & Guenther 2009, Sanchez & Yebra 2009, Paloczanska & Butler 2010, Cao *et al.* 2011). The most definitive statement that I encountered was in Radenovic *et al.* (2014) and Sørensen *et al.* (undated), who argued that fouling accumulation rates, and therefore the need for antifouling biocide, decrease with lower temperatures at the same rate that the biocide release rate of the paint they analyzed decreases. This, they claimed, makes the paint efficient, releasing the right amount of biocide that is needed at any temperature.

It's not clear, however, that fouling accumulation or severity decreases with lower temperatures and at higher latitudes. Many of the later publications cite WHOI (1952) as the source for this idea, but the WHOI book itself is vague about its own source and

seems a bit ambivalent about the claim. It does say that “it is generally considered” that fouling is more severe in the tropics, that fouling of ships’ piping is especially severe in the tropics, and that severe fouling is frequently associated with tropical ports, but the only source given for such statements is a reference to a British Admiralty design allowance for more rapid increase in frictional resistance from fouling growth in tropical than in temperate waters. The WHOI book also states that heavy fouling can develop in temperate regions during the summer, and that in a US-wide survey the greatest accumulation of fouling on navigation buoys was at Woods Hole in Massachusetts, at 41.5° N. Benson *et al.* (1973) similarly reported that "fouling is generally accepted to be more severe in the tropics than in temperate zones," but then stated that this is questionable because some tropical regions have lighter fouling than temperate regions. J.A. Lewis (pers. comm. 7/23/2018) reports that in Australia biofouling settlement and growth rates are higher in warm temperate waters than in tropical waters.

Two studies provide limited support for the claim that fouling intensity decreases with increasing latitude. Barnes (2002) reported a strong latitudinal cline in both hemispheres in the incidence of fouling on debris found washed ashore on islands, with no fouling on debris poleward of 50° N or 60° S. Davidson *et al.* (2014), sampled fouling on ships arriving in southern California and reported “a significant positive correlation between tropical port visits and occurrence of biofouling." However, this was based on a sample of only 9 ships, varying in type of ship, ship speeds, type of fouling paint, freshwater port visits, Panama Canal transits, and other factors that could affect fouling.

In contrast, Canning-Clode & Wahl (2010) reviewed data from 23 studies in 16 locations, in which fouling panels were deployed and analyzed using the same set of protocols. They found no evidence of a latitudinal cline in the rate of fouling growth. The highest rate of fouling overall was in Chile (29° S); the highest in the northern hemisphere was in Sweden (58° N).

Thus, despite many statements that fouling severity is greatest in the tropics and declines poleward, it is difficult to find data supporting this claim and some data contradict it. However, even if it were true that the amount and rate of growth of fouling is lower at lower temperatures, it doesn't necessarily mean that less biocide is needed to achieve a given level of protection against fouling. A biocidal antifoulant works if the release rate produces a biocide concentration next to the paint surface that equals or exceeds the critical lethal/deterrent concentration for the more biocide-tolerant species present. The need for biocide is thus likely to depend on the mix of biocide tolerances in the fouling species present rather than on the overall amount or rate of accumulation of fouling (J.A. Lewis, pers. com 7/12/2018).

In addition there is some evidence, at least for some biocides and some organisms, that the toxicity of biocides decreases with lower temperatures. For example, 3-4 times as much copper is needed to kill zebra mussels at 20°C than at 25°C (Rao & Khan 2000). If biocide toxicity is lower at lower temperatures, that would tend to increase rather than reduce the biocide release rate needed at higher latitudes and lower temperatures.

Discussion and Recommendations

Ballast Water and Hull Fouling

There are some similar challenges in managing the two main ship-associated invasion vectors, ballast water and hull fouling. For example, in both cases we are hampered in setting management targets by not knowing the shape of the invasion vs. release curve. For both ballast water and hull fouling, if we reduce the rate at which non-native species are released by, say, 99%, we simply do not know whether the rate of successful invasion will also fall by around 99%, or by some considerably larger or considerably smaller amount. Though we may be reasonably confident that with fewer non-native species released there will be fewer successful invasions, we don't know how much we need to reduce the rate of release in order to achieve any particular benefit.

There are some key differences between these two vectors, however. The task of treating ballast water is relatively straightforward: to remove or kill a diverse group of organisms trapped in a large tank of water. Treating hull fouling is much more complicated, because the organisms live outside the hull in constant contact with the environment. As a result, we have much less control over the circumstances and the consequences of treatment actions.

Government regulations are the primary driver of ballast water treatment. These include a test requirement and protocols for treatment systems, so that we have a set of more-or-less consistent (although deeply imperfect) performance data for most of the treatment systems available. In contrast, hull fouling treatment is primarily driven by market forces. There's no common test requirement and no set of data covering the performance of different antifouling paints. The development and utilization of these paints is geared toward the concerns of shipowners, not toward government concerns about protection of the environment and public health. Effective antifouling treatment from the perspective of the shipping industry may differ in critical ways from effective antifouling treatment to prevent bioinvasions.

The relative complexity of treating hull fouling to prevent invasions means that a one-size-fits-all approach, or even a few-sizes-fit-all approach, may not be adequate. To be effective, management actions may need to be closely tailored to each individual vessel and its pattern of shipping routes and layover periods, to a degree that is not necessary with ballast water. To do this, better and more comprehensive information on the performance of antifouling coatings under a range of environmental conditions will be needed. This information is unlikely to be spontaneously developed and made public by the marketplace. Instead, it will require government action, either by requiring manufacturers to develop and release the information, or by funding the necessary testing and research directly.

Given the challenges of addressing the biofouling invasion risk, government agencies may need to distinguish among different groups of vessels and focus efforts on the ships that pose the greatest risks, or on the ships where government action can have the greatest impact. Relevant distinguishing characteristics may include vessel type,

vessel speed, pattern of voyages and layovers, voyage origin, time since last application of antifouling paint, fouling coverage, etc.

Sea Ice and Ice-free Seas

For biofouling in the Arctic, it will be helpful to distinguish, first, between ships that transit through sea ice and ships that sail in ice-free seas. For the former, the choices are complicated. Passing through substantial sea ice can clean most of the fouling off a hull, and one author even suggests that ships that might otherwise avoid sea ice should consider seeking it out and passing through it as a means of reducing the risk of bioinvasions.[16] However, passing through sea ice can have undesirable bioinvasion consequences, including releasing potential invaders into the water and removing a substantial part of a ship's antifouling coating. For ships whose routes and schedules will take them through sea ice, relying on antifouling paint to reduce invasion risk may not be tenable.

Some Antarctic research vessels and icebreakers in the Arctic apply antifouling paint only to areas that are protected against ice abrasion (*e.g.* sea chests, thrusters), with the rest of the hull painted with an abrasion-resistant epoxy-based coating (Lewis *et al.* 2003, 2004; Chan *et al.* 2012). These hard coatings can be used with various in-water cleaning systems (Finnie & Williams 2010), and some are specifically designed for use in sea ice (Subsea Industries undated). Though not a perfect solution, the use of a durable, epoxy-based coating on the hull, with antifoulant on areas protected from ice scour, combined with a schedule of in-water hull cleaning (especially after long layovers in port before putting to sea) may be a reasonable best management practice for ships that pass through sea ice.

Antifouling, Temperature and Latitude

For ships traveling in the Arctic through ice-free water, the selection of an effective antifouling paint is critical. However, little information is available to help make that selection. In this review I found no information on how any direct measure of fouling reduction varies with water temperature and latitude. I did find some data on how biocide release rates and polishing rates (which affect biocide release rates) change with temperature. Compilation and analysis of the data shows that these changes are often large, and in particular that biocide release rates are often substantially lower at lower temperatures (Figs. 4, 5).

Manufacturers typically test their antifouling paints in tropical to cold temperate waters (J.A. Lewis, pers. comm. 7/26/2018). To prevent hull fouling invasions in the Arctic, an antifouling paint would have to at least perform effectively at the water temperatures that typically occur in the summertime (when most of the shipping activity within the Arctic occurs) in the northern Temperate Zone (to prevent North Temperate-to-Arctic invasions), and in the Subarctic and Arctic Core regions (to prevent Arctic-to-Arctic

[16] "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" (Hughes & Ashton 2017).

invasions). Typical temperatures for these regions are shown in Table 2. If a paint is tested at a site in the cold temperate, subtropical or tropical region, and releases the right amount amount of biocide to perform well at that site, it will release only a fraction of that amount at a Subarctic or Arctic Core site, based on the array of paints profiled in Figs. 4 and 5.

Table 2. Typical average surface water temperatures (°C) in northern hemisphere regions. Arctic Core and Subarctic regions as described in the text; other region boundaries are derived from Ekman (1953), with temperatures from Sverdrup *et al.* (1942).

Region	Summer	Winter
Arctic Core	≤5°	-2° to 0°
Subarctic	mainly 5-10°, sometimes to 13°	mostly ≤2°, sometimes to 8°
Cold Temperate	mostly 10-17°, sometimes to 25°	-1° to mostly <10°, sometimes to 15°
Warm Temperate	16-23°, sometimes to 27°	10-18°
Tropical/Subtropical	mostly 20-28°, sometimes ≥15° or ≤33°	

As discussed earlier, several papers in the biofouling literature either imply or state outright that less biocide is needed in colder waters in order to achieve a given level of fouling control, and that this compensates partly or completely for the reduction in biocide released by antifouling paints in colder waters. The argument is that fouling is less intense in colder waters, and that therefore less biocide should be needed to control it. My review did not find support for either part of this argument. On balance, the published literature does not show that biofouling decreases with higher latitudes and colder waters. While I found a couple of papers with data that fit a pattern of a decrease in fouling with latitude, other papers provided data that did not. I also did not find any data to support the second element of the argument, that where fouling is less intense it can be controlled with a lower biocide release rate.

Instead, what governs how much biocide is needed may be the biocide tolerances of the fouling species present, not the amount of fouling or its rate of growth (J.A. Lewis, pers. comm. 7/12/2008). It's possible that there is a latitudinal cline in biocide tolerance—for example, the lower species diversity of biofouling at higher latitudes (Canning-Clode & Wahl 2010) could mean a narrower range of biocide tolerances at those latitudes, and thus fewer highly tolerant species. Alternatively, it's possible that centuries of applying antifouling compounds and metal cladding to ship hulls has selected for more biocide tolerant (and perhaps, particularly, more metals-tolerant) organisms. The more tolerant species would have been spread widely, especially to the older and larger ports. As there are more such ports in the mid and lower latitudes than at high latitudes, this could result in a decrease in biocide tolerance and thus a decrease in the level of biocide needed at higher latitudes. At present these are only theories, and would need to be tested. Finally, there are some data that suggest that certain biocides may be more toxic in warmer water (*e.g.* Rao & Khan 2000); this would contribute to the opposite trend, that is, a need for a higher biocide release rate in colder water.

In summary, there are consistent data showing that the rate of biocide release from antifouling paints decreases substantially with lower temperatures, and there is no evidentiary basis for the oft-implied and occasionally articulated position that there is a decline in the need for biocide with lower water temperatures, which compensates for the reduced biocide release. Rather, I found no direct information on how temperature affects the need for biocide, and there are a number of factors that could contribute to a latitudinal trend in one direction or the other. This seems like an important set of questions, given the influence of temperature on the various processes that contribute to the antifouling effect, and a greater effort should be made to answer them.

Shipping and Layover Patterns

Antarctic research vessels and supply ships (and possibly some tourism cruise ships) have a typical sailing schedule that entails a busy summer season moving people and material to and from stations on the Antarctic continent and subantarctic islands and/or conducting research cruises, with only short layovers between trips. In the winter they retreat to lower latitudes, and some ships may spend the entire winter period laid up at one port, during which time they can accumulate a heavy cover of fouling (Lewis *et al.* 2003; Lee & Chown 2009). This suggests a set of risk management actions tailored to this shipping pattern, such as repairing/replacing antifouling coatings each winter, or scheduling a hull cleaning before the first voyage of the summer season each year to remove the winter fouling accumulation. If there are similar or other shipping patterns that are typical in parts of the Arctic, it would be useful to identify and describe them, and identify a schedule of management actions that would best reduce the risk of biofouling invasions.

In a previous report I suggested that vessels that remain in one location for an extended period, travel slowly to a distant location, and then remain in the new location for an extended period likely pose a higher risk of invasions (Cohen 2016). These may include barges, semi-submersible drilling platforms, recently purchased vessels, ships temporarily out of service, and certain charter vessels. Such vessels may carry an extensive and well-developed fouling community (Bercaw 1993; DeFelice 1999; Coutts 2002; Davidson *et al.* 2008, Wanless *et al.* 2010). Ideally, this type of vessel would be identified and its hull thoroughly cleaned before departing for the Arctic or shifting its location within the Arctic.

New Zealand's nationwide biofouling control standard went into effect earlier this year. Under that standard, vessels that have remained stationary for an extended period of time or that have been moving at low speeds in coastal waters are designated as high risk, and are required to take specific management actions including cleaning the hull before entering New Zealand waters (New Zealand 2018). These and other elements of the New Zealand standard should be reviewed and considered for Arctic waters.

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Literature Cited

Almeida E, Diamantino TC, De Sousa O. 2007. Marine paints: the particular case of antifouling paints. *Progress in Organic Coatings* 59(1): 2-20.

AMAP. 1998. *AMAP Assessment Report: Arctic Pollution Issues*. Arctic Council, Arctic Monitoring and Assessment Programme, Oslo, Norway.

Barnes DK. 2002. Invasions by marine life on plastic debris. *Nature* 416: 808-809.

Benson PH, Brining DL, Perrin DW. 1973. Marine fouling and its prevention. *Marine Technology* 10(1): 30-37.

Bercaw SS. 1993. *The Role Played by Semisubmersible Exploratory Drilling Platforms as a Vector in Marine Biological Introductions*. MA thesis, Marine Affairs, University of Rhode Island.

Berge J, Johnsen G, Nilsen F, Gulliksen B, Slagstad D. 2005. Ocean temperature oscillations enable reappearance of blue mussels *Mytilus edulis* in Svalbard after a 1000 year absence. *Marine Ecology Progress Series* 303:167-175.

California SLC. 2013. *California's Marine Invasive Species Program and the United States Federal Programs that Manage Vessels as Vectors of Nonindigenous Species: A Comparison of the Relative Effectiveness at Reducing the Risk of Nonindigenous Species Introduction from Maritime Shipping Activities*. California State Lands Commission Marine Facilities Division, Sacramento, California, USA.

Canning-Clode J, Wahl M. 2010. Patterns of fouling on a global scale. Pages 73-86 in: *Biofouling*, Dürr S, Thomason JC (eds.), Wiley-Blackwell, Chichester, West Sussex, United Kingdom.

Cao S, Wang J, Chen H, Chen D. 2011. Progress of marine biofouling and antifouling technologies. Chinese Science Bulletin 56(7): 598-612.

Chambers LD, Stokes KR, Walsh FC, Wood RJ. 2006. Modern approaches to marine antifouling coatings. *Surface and Coatings Technology* 201(6): 3642-3652.

Champ MA, Seligman PF. 1996. An introduction to organotin compounds and their use in antifouling coatings. Pages 1-25 in: *Organotin*, Champ MA, Seligman PF (eds.), Chapman & Hall, London

Chan FT, Bronnenhuber JE, Bradie JN, Howland KL, Simard N, Bailey SA. 2012. *Risk Assessment for Ship-Mediated Introductions of Aquatic Nonindigenous Species to the Canadian Arctic*. Canadian Science Advisory Secretariat, Department of Fisheries and Oceans, Ottawa, Ontario, Canada.

Chan FT, MacIsaac HJ, Bailey SA. 2015. Relative importance of vessel hull fouling and ballast water as transport vectors of nonindigenous species to the Canadian Arctic. *Canadian Journal of Fisheries and Aquatic Sciences* 72(8): 1230-1242.

Chan FT, MacIsaac HJ, Bailey SA. 2016. Survival of ship biofouling assemblages during and after voyages to the Canadian Arctic. *Marine Biology* 163(12): 250.

Christie P, Sommerkorn M. 2012. *RACER: Rapid Assessment of Circum-arctic Ecosystem Resilience*. 2nd Edition. World Wildlife Fund, Global Arctic Programme, Ottawa, Ontario, Canada.

Clayton MN, Wiencke C, Klöser H. 1997. New records of temperate and sub-Antarctic marine benthic macroalgae from Antarctica. *Polar Biology* 17(2): 141-149.

Cohen AN. 2016. *White Paper on Ship-mediated Bioinvasions in the Arctic: Pathways and Control Strategies*. A report for Friends of the Earth International. Center for Research on Aquatic Bioinvasions, Richmond, California, USA. MEPC 69/INF.17 by FOEI, 9 Feb. 2016.

Cohen AN. 2017. *An Assessment of Ballast Water Treatment to Protect Arctic Waters*. A report for Friends of the Earth US. Center for Research on Aquatic Bioinvasions, Richmond, California, USA. MEPC 72/INF.7 by FOEI, 8 Jan. 2018.

Cordell J, Sosik E, Faulkner M, Scianni C. 2009. *Characterizing Risk Associated with Vessel Fouling and Nonindigenous Species in Prince William Sound*. Prepared for the Prince William Sound Regional Citizens' Advisory Council, Valdez, Alaska, USA.

Coutts ADM. 2002. *A Biosecurity Investigation of a Barge in the Marlborough Sounds*. Cawthron Report No. 744, Cawthron, Nelson, New Zealand.

Coyer JA, Hoarau G, Skage M, Stam WT, Olsen JL. 2006. Origin of *Fucus serratus* (Heterokontophyta; Fucaceae) populations in Iceland and the Faroes: a microsatellite-based assessment. *European Journal of Phycology* 41(2): 235-246.

Dafforn KA, Lewis JA, Johnston EL. 2011. Antifouling strategies: history and regulation, ecological impacts and mitigation. *Marine Pollution Bulletin* 62(3): 453-465.

Davidson I, McCann LD, Sytsma MD, Ruiz GM. 2008. Interrupting a multi-species bioinvasion vector: the efficacy of in-water cleaning for removing biofouling on obsolete vessels. *Marine Pollution Bulletin* 56(9): 1538-1544.

Davidson I, Scianni C, Ceballos L, Zabin C, Ashton G, Ruiz G. 2014. Evaluating ship biofouling and emerging management tools for reducing biofouling-mediated species incursions. Report for the Marine Invasive Species Program of the California State Lands Commission, Sacramento, California, USA. Aquatic Bioinvasion Research & Policy Institute, Portland State University, Portland Oregon, USA.

Davidson I, Sytsma M, Ruiz G. 2006. *Preliminary Investigations of Biofouling of Ships' Hulls: Non-Indigenous Species Investigations in the Columbia River*. Report for U.S. Coast Guard. Aquatic Bioinvasion Research & Policy Institute, Portland State University, Portland, Oregon, USA.

Dayton PK. 1989. Interdecadal variation in an Antarctic sponge and its predators from oceanographic climate shifts. *Science* 245(4925): 1484-1486.

DeFelice RC. 1999. *Fouling Marine Invertebrates on the Hull of the USS Machinist in Pearl Harbor Prior to its Move to Apra Harbor, Guam*. Final report submitted to US Fish and Wildlife Service, Pacific Islands Ecoregion, Honolulu, Hawai'i. Hawaii Biological Survey Contribution 13.

De la Court FH, De Vries HJ. 1973. Advances in fouling prevention. *Progress in Organic Coatings* 1(4): 375-404.

De Nys R, Guenther J. 2009. The impact and control of biofouling in marine finfish aquaculture. Pages 177-221 in: Hellio C, Yebra DM (eds.), *Advances in Marine Antifouling Coatings and Technologies*, CRC Press, Boca Raton, Boston, New York and Washington, DC, USA and Woodhead Publishing Limited, Oxford, Cambridge, United Kingdom and New Delhi, India.

Ekman S. 1953. *Zoogeography of the Sea*. Sidgwick & Jackson, Ltd., London, United Kingdom.

Ferry JD, Carritt DE. 1946. Action of antifouling paints: solubility and rate of solution of cuprous oxide in seawater. *Industrial and Engineering Chemistry* 38: 612-617.

Finnie AA, Williams DN. 2010. Paint and coatings technology for the control of marine fouling. Pages 185-206 in: *Biofouling*, Dürr S, Thomason JC (eds.), Wiley-Blackwell, Chichester, West Sussex, United Kingdom.

Griffiths HJ, Whittle RJ, Roberts SJ, Belchier M, Linse K. 2013. Antarctic crabs: invasion or endurance? *PLoS One* 8(7): e66981.

Hagan P, Price E, King D. 2014. *Status of Vessel Biofouling Regulations and Compliance Technologies - 201*4. MERC Economic Discussion Paper 14-HF-01. http://www.maritime-enviro.org/Downloads/Reports/Other_Publications/Status_of_Vessel_Biofouling_Regs_2014_%20Nov_18_2014.pdf, accessed 7/24/2018.

Hughes KA, Ashton GV. 2016. Breaking the ice: the introduction of biofouling organisms to Antarctica on vessel hulls. *Aquatic Conservation: Marine and Freshwater Ecosystems* 27(1): 158-164.

IMO. 2001. *International Convention on the Control of Harmful Antifouling Systems on Ships*. International Maritime Organization, London, United Kingdom.

IMO. 2011. 2011 *Guidelines for the Control and Management of Ships' Biofuling to Minimize the Transfer of Invasive Aquatic Species*. Resolution MEPC.207(62), International Maritime Organization, Marine Environmental Protection Committee, London, UK.

IMO. 2012. *Guidance for Minimizing the Transfer of Invasive Aquatic Species as Biofouling (Hull Fouling) for Recreational Craft*. MEPC.1/Circ.792, International Maritime Organization, Marine Environmental Protection Committee, London, UK.

IMO. 2013. *Guidance for Evaluating the 2011 Guidelines for the Control and Management of Ships' Biofuling to Minimize the Transfer of Invasive Aquatic Species*. MEPC.1/Circ.811, International Maritime Organization, Marine Environmental Protection Committee, London, UK.

Johansson S. 2013. *Arctic Vessels: Anti-fouling and other Traditional Ship Bottom Covering Concepts*. Nauticapedia website. http://www.nauticapedia.ca/Articles/Ship_Bottom.php, accessed 7/8/2018.

Kiil S, Weinell CE, Pedersen MS, Dam-Johansen K. 2002a. Mathematical modelling of a self-polishing antifouling paint exposed to seawater: a parameter study. *Chemical Engineering Research and Design* 80(1): 45-52.

Kiil S, Weinel CE, Pedersen MS, Dam-Johansen K, Arias Codolar S. 2002b. Dynamic simulations of a self-polishing antifouling paint exposed to seawater. *Journal of Coatings Technology* 74 (929): 45-54.

Kiil S, Dam-Johansen K, Weinell CE, Pedersen MS. 2002c. Seawater-soluble pigments and their potential use in self-polishing antifouling paints: simulation-based screening tool. *Progress in Organic Coatings* 45(4): 423-434.

Lee JE, Chown SL. 2009. Temporal development of hull-fouling assemblages associated with an Antarctic supply vessel. *Marine Ecology Progress Series* 386: 97-105.

Lewis JA. 1998. Marine biofouling and its prevention on underwater surfaces. *Materials Forum* 22: 41-61.

Lewis JA, Coutts ADM. 2010. Biofouling Invasions. Pages 348-365 in: *Biofouling*, Dürr S, Thomason JC (eds.), Wiley-Blackwell, Chichester, West Sussex, United Kingdom.

Lewis PN, Hewitt CL, Riddle M, McMinn A. 2003. Marine introductions in the Southern Ocean: an unrecognised hazard to biodiversity. *Marine Pollution Bulletin* 46(2): 213-223.

Lewis PN, Riddle MJ, Hewitt CL. 2004. Management of exogenous threats to Antarctica and the sub-Antarctic Islands: balancing risks from TBT and non-indigenous marine organisms. *Marine Pollution Bulletin* 49(11-12): 999-1005.

Lindgren JF, Wilewska-Bien M, Granhag L, Andersson K, Eriksson KM. 2016. Discharges to the Sea. Pages 125-168 in: *Shipping and the Environment: Improving Environmental Performance in Marine Transportation*, Andersson K, Brynolf S, Lindgren JF, Wilewska-Bien M (eds.), Springer-Verlag, Berlin and Heidelberg, Germany.

Marson F. 1969. Anti-fouling paints. I. Theoretical approach to leaching of soluble pigments from insoluble paint vehicles. *Journal of Chemical Technology and Biotechnology* 19(4): 93-99.

Matsson S, Metaxas A, Bluhm B, Christie H, Fieler R, Forbord S, Handå A. 2018. *Seaweed Cultivation above the Arctic Circle*. Presented at: Arctic Frontiers, 23 July 2018, Tromsø, Norway. https://www.sintef.no/en/publications/publication/?pubid=CRIStin+1558833, accessed 7/13/2018.

McCoy EJA, Johnson LT. 1995. *Selecting a Hull Paint for Your Boat*. University of California Cooperative Extension, SeaGrant Extension Program, San Diego, California, USA.

Meyer KS, Sweetman AK, Kuklinski P, Leopold P, Vogedes D, Berge J, Griffiths C, Young CM, Renaud PE. 2017. Recruitment of benthic invertebrates in high Arctic fjords: Relation to temperature, depth, and season. *Limnology and Oceanography* 62(6): 2732-2744.

Nandakumar K, Yano T. 2003. Biofouling and its prevention: A comprehensive overview. *Biocontrol Scienc*e 8(4): 133-144.

Negri AP, Hales LT, Battershill C, Wolff C, Webster NS. 2004. TBT contamination identified in Antarctic marine sediments. *Marine Pollution Bulletin* 48(11-12): 1142-1144.

Negri A, Marshall P. 2009. TBT contamination of remote marine environments: Ship groundings and ice-breakers as sources of organotins in the Great Barrier Reef and Antarctica. *Journal of Environmental Management* 90: S31-S40.

New Zealand. 2018. *Guidance Document for the Craft Risk Management Standard for Biofouling*. GD CRMS-BIOFOUL, Ministry for Primary Industries, New Zealand Government., Wellington, New Zealand.

OSPAR. 2000. *Quality Status Report 2000: Region I. Arctic Waters*. OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic, London, United Kingdom.

PAME. 2013. *Large Marine Ecosystems (LMEs) of the Arctic Area: Revision of the Arctic LME Map*. 2nd Edition. Arctic Council, Protection of the Arctic Marine Environment, Akureyri, Iceland.

Pei X, Ye Q. 2015. Development of marine antifouling coatings. Pages 135-149 in: *Antifouling Surfaces and Materials*, Zhou F (ed.), Springer, Berlin and Heidelberg, Germany.

Pereira M, Ankjaergaard C. Legislation affecting antifouling products. 2009. Pages 240-259 in: *Advances in Marine Antifouling Coatings and Technologies*, Hellio C, Yebra DM (eds.), CRC Press, Boca Raton, Boston, New York and Washington, DC, USA and Woodhead Publishing Limited, Oxford, Cambridge, United Kingdom and New Delhi, India.

Poloczanska ES, Butler AJ. 2010. Biofouling and climate change. Pages 333-347 in: *Biofouling*, Dürr S, Thomason JC (eds.), Wiley-Blackwell, Chichester, West Sussex, United Kingdom.

Radenovic J, Sørensen KF, Yebra DM, Blom A, Hillerup D, Olsen SM. 2014. *New Technology for Fouling Defense: Fusion of Biocide and Hydrogel-Based Technologie*s. Corrosion 2014, International Corrosion Conference, March 9-13, 2014, San Antonio,Texas, NACE International.

Rao DGV, Khan MAQ. 2000. Zebra mussels: enhancement of copper toxicity by high temperature and its relationship with respiration and metabolism. *Water Environment Research* 72(2): 175-178.

Sanchez A, Yebra DM. 2009. Ageing tests and long-term performance of marine antifouling coatings. Pages 393-421 in: *Advances in Marine Antifouling Coatings and Technologies*, Hellio C, Yebra DM (eds.), CRC Press, Boca Raton, Boston, New York and Washington, DC, USA and Woodhead Publishing Limited, Oxford, Cambridge, United Kingdom and New Delhi, India.

SCAR. 2007. Hull fouling as a source of marine invasion in the Antarctic. Agenda Item ATCM 13, CEP 8(a), Scientific Committee on Antarctic Research, submitted to the Committee for Environmental Protection, 30th Antarctic Treaty Consultative Meeting, New Delhi, April 30 to May 11, 2007. https://www.scar.org/antarctic-treaty/actm-papers/atcm-xxx-and-cep-x-2007/2908-atcm30-ip037/, accessed July 3, 2018.

Schatzberg P. 1996. Measurement and significance of the release rate for tributyltin. Pages 383-403 in: *Organotin*, Champ M.A, Seligman PF (eds.), Chapman & Hall, London.

Schultz MP. 2007. Effects of coating roughness and biofouling on ship resistance and powering. *Biofouling* 23(5): 331-341.

Sherman K, Hempel G (eds.). 2009. *The UNEP Large Marine Ecosystem Report: A Perspective on Changing Conditions in LMEs of the World's Regional Seas*. UNEP Regional Seas Report and Studies No. 182, United Nations Environment Programme. Nairobi, Kenya.

Sirenko BI, Clarke C, Hopcroft RR, Huettmann F, Bluhm BA, Gradinger R. (eds). 2018. The Arctic Register of Marine Species (ARMS), compiled by the Arctic Ocean Diversity (ArcOD). http://www.marinespecies.org/arms, accessed 7/10/2018.

Sørensen KF, Hillerup D, Blom A, Olsen SM. Undated. *ActiGuard®: Novel Technology to Improve Long-Term Performance of Silicone-based Fouling Defence Coatings*. http://www.hempel.com/~/media/Sites/hempel/files/marine/technical-papers/ActiGuardtechnology.pdf, accessed 5/20/2018.

Spalding MD, Fox HE, Allen GR, Davidson N, Ferdaña ZA, Finlayson MA, Halpern BS, Jorge MA, Lombana AL, Lourie SA, Martin KD. 2007. Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. *BioScience* 57(7): 573-583.

Subsea Industries. Undated. *Ecospeed® for Ice*. Brochure, Subsea Industries, Antwerpt, Belgium.

Sverdrup HU, Johnson MW, Flemming RH. 1942.*The Oceans: Their Physics, Chemistry and General Biology*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, USA.

Sylvester F, Kalaci O, Leung B, Lacoursière-Roussel A, Murray CC, Choi FM, Bravo MA, Therriault TW, MacIsaac HJ. 2011. Hull fouling as an invasion vector: can simple models explain a complex problem? *Journal of Applied Ecology* 48(2): 415-423.

Tavares M, De Melo GA. 2004. Discovery of the first known benthic invasive species in the Southern Ocean: the North Atlantic spider crab *Hyas araneus* found in the Antarctic Peninsula. *Antarctic Science* 16(2):129-131.

Thatje S. 2005. The future fate of the Antarctic marine biota? *Trends in Ecology and Evolution* 20(8): 418-419.

Thomas K, Raymond K, Chadwick J, Waldock M. 1999. The effects of short-term changes in environmental parameters on the release of biocides from antifouling coatings: cuprous oxide and tributyltin. *Applied Organometallic Chemistry* 13(6): 453-460.

Thorarinsdottir G, Gunnarsson K, Gíslason OS. 2014. Invasive Species: Case studies from Iceland. Pages 83-109 in: *Marine Invasive Species in the Arctic*, Nordic Council of Ministers.

Timmermans ML. 2016. Sea surface temperatures. Pages 46-49 in: *Arctic Report Card 2016*, Richter-Menge J, Overland JE, Mathis JT (eds.), National Oceanic and Atmospheric Administration, Washington, DC, USA. http://www.arctic.noaa.gov/Report-Card, accessed 4/18/2018.

Timmermans ML, Ladd C, Wood K. 2017. Sea surface temperatures. Pages 34-38 in: *Arctic Report Card 2017*, Richter-Menge J, Overland JE, Mathis JT, Osborne E (eds.), National Oceanic and Atmospheric Administration, Washington, DC, USA. http://www.arctic.noaa.gov/Report-Card, accessed 4/18/2018.

Timmermans ML, Proshutinsky A. 2014. Sea surface temperatures. Pages 39-43 in: *Arctic Report Card 2014*, Jeffries OM, Richter-Menge J, Overland JE (eds.), National Oceanic and Atmospheric Administration, Washington, DC, USA. http://www.arctic.noaa.gov/Report-Card, accessed 4/18/2018.

Timmermans ML, Proshutinsky A. 2015. Sea surface temperatures. Pages 41-43 in: *Arctic Report Card 2015*, Jeffries OM, Richter-Menge J, Overland JE (eds.), National Oceanic and Atmospheric Administration, Washington, DC, USA. http://www.arctic.noaa.gov/Report-Card, accessed 4/18/2018.

Van Londen AM. 1963. *A Study of Ship Bottom Paints, in Particular Pertaining to the Behaviour and Action of Anti-fouling Paints*. Report 54C of Netherlands' Research Center TNO for Shipbuilding and Navigation, Delft, The Netherlands.

Wanless RM, Scott S, Sauer WH, Andrew TG, Glass JP, Godfrey B, Griffiths C, Yeld E. 2010. Semi-submersible rigs: a vector transporting entire marine communities around the world. *Biological Invasions* 12(8): 2573-2583.

Ware C, Alsos IG, Berge J, Sundet JH, Arneberg P. 2012. *Ships as Potential Dispersal Vectors of Invasive Marine Organisms into High-Arctic Svalbard*. University of Tromsø, Tromsø, Norway.

WHOI. 1952. *Marine Fouling and its Prevention*. Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA, and United States Naval Institute, Annapolis, Maryland, USA.

Witman JD, Etter RJ, Smith F. 2004. The relationship between regional and local species diversity in marine benthic communities: A global perspective. *Proceedings of the National Academy of Sciences* 111 (44): 15664-15669.

Yebra DM, Kiil S, Dam-Johansen K. 2004. Antifouling technology—past, present and future steps towards efficient and environmentally friendly antifouling coatings. *Progress in Organic Coatings* 50(2): 75-104.

Yebra DM, Kiil S, Dam-Johansen K, Weinell C. 2005. Reaction rate estimation of controlled-release antifouling paint binders: rosin-based systems. *Progress in Organic Coatings* 53(4): 256-275.

Yebra DM, Kiil S, Weinell CE, Dam-Johansen K. 2006. Mathematical modeling of tin-free chemically-active antifouling paint behavior. *AIChE Journal* 52(5): 1926-1940.

Yebra DM, Weinell CE. 2009. Key issues in the formulation of marine antifouling paints. Pages 308-333 in: *Advances in Marine Antifouling Coatings and Technologies*, Hellio C, Yebra DM (eds.), CRC Press, Boca Raton, Boston, New York and Washington, DC, USA and Woodhead Publishing Limited, Oxford, Cambridge, United Kingdom and New Delhi, India.