# Title: What limits bioinvasions in the Arctic? Investigating the role of cold water temperatures on the survival and reproduction of non-native taxa in the Bering Sea

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# Abstract

Cold water temperatures and minimal shipping traffic are expected to limit biological introductions in polar ecosystems, but these expectations across multiple taxa and life stages have rarely been evaluated. We examined patterns of shipping traffic, and the role of water temperatures on the potential survival and reproductive habitat of 42 non-indigenous species (NIS) in the Bering Sea, a marine ecosystem characterized by a strong, subarctic-arctic latitudinal gradient. We built habitat suitability models by comparing species’ temperature and salinity thresholds to conditions in the Bering Sea projected by three regional ocean models, and investigated the effect of climate change by considering two time periods: current (2003-2012) and mid-century (2030-2039). Additionally, we quantified traffic from commercial and fishing vessels, and ballast water discharge, to U.S. Bering Sea ports. Under current conditions, areas north of 58°N, where winter water temperatures are below 0°C, were largely inhospitable for NIS. In contrast, the southeastern Bering Sea was predicted to be highly suitable for the year-round survival of 83% of the taxa assessed (*n*=42). Suitable reproductive temperatures also exist for many of the taxa considered, but the short summer season may limit those that require temperatures above 10ºC for development. By 2039, models predict a northward expansion of suitable habitat, largely favoring taxa that already have the ability to survive year-round. Areas of high habitat suitability is also home to the port of Dutch Harbor, which received the greatest amount of vessel traffic and ballast water discharge, and which serves as a hub connected to local ports throughout the Bering Sea. The southeastern Bering Sea, and the port of Dutch Harbor in particular, are high-risk areas for biological introductions and should be monitored.

by developing species-specific habitat suitability models and quantifying vessel traffic we were able to determine spatial risk

**Key words:** Arctic, climate change, physiological thresholds, habitat suitability, biological invasion, marine, non-native species, shipping, Bering Sea, Alaska, risk assessment

# Introduction

Vessel traffic, water temperature, and salinity are strong, predictive factors of the distribution of aquatic organisms (Hewitt and Hayes 2002, Barry et al. 2008, Lord et al. 2015). It is no surprise, then, that in today’s warming, hyper-connected oceans, the distribution of marine species is changing at an exhilarating pace (Seebens et al. 2017). Given the potential for impacts to fisheries, local livelihoods, and native ecosystems, risk assessments that reveal which areas are most at risk of invasion, and which non-indigenous species (NIS) pose the biggest threat, are becoming essential components of aquatic ecosystem management (Mandrak and Cudmore 2015). Nowadays, ships are the main vectors by which NIS are transported to new regions (Ruiz et al. 1997, Molnar et al. 2008), ports and regions with high shipping traffic are predicted to be more at risk than low-traffic regions. High rates of introductions, either in terms of events or organism numbers, increase the probability of NIS surviving and establishing populations in new regions, though this relationship is not without its complexities (Verling et al. 2005). Factors such as the port of origin, the route taken, the duration of the voyage, the type of ship, and the difference in environmental conditions between origin and recipient ports, collectively influence the diversity, number, and success of these introductions (Verling et al. 2005, Colautti et al. 2006, Miller and Ruiz 2014). Meanwhile, water temperatures determine post-transport survival and establishment, especially for ectotherms in cold water systems (Ruiz and Hewitt 2009). Water temperatures above or below optimal thresholds can have a negative effect on behavioural, metabolic, and cellular processes; if temperatures exceed a critical threshold, mortality ensues (Pörtner 2001, Kassahn et al. 2009). Even species that can survive in cold waters may not be able to establish a self-sustaining population, as reproduction, development, and growth can have narrower thermal ranges than survival (Woodin et al. 2013).

Arctic systems have historically experienced relatively low rates of invasion, and it is generally assumed that this results from low vessel traffic and cold water temperatures. However, these assertions have not often been explored. Recent studies have shown that several NIS are being transported from temperate regions to Arctic ports in ballast water and on wetted surfaces, and are surviving the voyage (Chan et al. 2014, 2016, Ware et al. 2016). Most ecological studies that have quantified shipping traffic to Arctic regions have focused on the potential for introductions from ballast water, which is transported by large vessels such as those involved with commercial, military, tourism, or research activities (McGee et al. 2006, Chan et al. 2013, Verna et al. 2016, Ware et al. 2016). The role of smaller vessels such as fishing vessels, tugs, and ferries, has largely been overlooked (but see Chan et al. 2016). These vessels may not carry ballast water, but may still introduce new species to a region via biofouling, and the risk posed by biofouling may exceed the risk posed by ballast water (Chan et al. 2015). Moreover, despite the potentially large number of species that are being transported, multi-species studies of habitat suitability remain rare, and have typically focused on a very small subset of the total species that may be introduced to Arctic regions (de Rivera et al. 2011, Ware et al. 2016, Goldsmit et al. 2018). Only one (Ware et al. 2016) modeled whether habitat was suitable for reproduction, an essential component to assessing whether species can establish self-sustaining populations. These studies have concluded that potentially suitable habitat exists for at least some NIS, but have come to different conclusions about whether suitable habitat is extensive (de Rivera et al. 2011) or limited (Ware et al. 2016, Goldsmit et al. 2018). Our understanding of whether Arctic conditions limit biological invasions remains incomplete.

There is an increasing need to understand the role of temperature in limiting biological introductions to the Arctic because both Arctic sea temperatures and trans-oceanic vessel traffic are expected to increase in the near-future. In recent decades, the Arctic has experienced record-setting declines in sea ice thickness and extent, and surface air temperatures have increased at a rate that is twice that of the global average (Lemke et al. 2007, Stroeve et al. 2012). Warming sea temperatures and sea ice reductions have facilitated range expansions and introductions into previously inhospitable or inaccessible waters elsewhere (Reid et al. 2007, Renaud et al. 2015), and distribution models predict that Arctic waters will become even more suitable to invasions over the next century (de Rivera et al. 2011, Ware et al. 2014, 2016). Warming climatic conditions have also favoured expansions in global shipping and other human activities. Since the beginning of the 21st century, there has been an exponential increase in Arctic shipping, spurred in part by declining sea ice extent and lengthening of ice-free season (Miller and Ruiz 2014, Eguíluz et al. 2016). In addition to commercial vessel traffic, the Arctic is also expected to see different types of ships and activities, such as natural resource exploration and extraction, and Arctic tourism. Changes in traffic volume and patterns are expected to increase the number and diversity of organisms that are being transported to Arctic regions.

In this paper, we explore whether cold water temperatures have the potential to limit introductions in the Arctic by examining whether NIS had thresholds that would allow them to survive and reproduce in the Bering Sea, a high-latitude marine ecosystem characterized by a strong, latitudinal gradient. We also quantify vessel traffic and ballast water discharge for U.S. ports in the Bering Sea to identify potential entry points of NIS, and to consider the interplay of traffic and habitat suitability. We hypothesized that survival would depend on species’ tolerance to cold water temperatures, and predicted that potential NIS richness would be higher in the southern Bering Sea, and decline in the north. Because climate change is expected to increase water temperatures in the Bering Sea, we predicted that habitat would become more suitable for NIS in the future. To address this hypothesis, we examine current and mid-century marine temperature regimes across the Bering Sea and characterize survival and reproductive habitat for potential NIS. Our work extends previous research by providing a comprehensive assessment of the role of temperature on high-latitude invasions based on a understanding of NIS physiological tolerances, modeled ocean conditions and available data on vessel and ballast water movements.

# Methods

## Study area

The Bering Sea lies between the temperate North Pacific Ocean and the arctic waters of the Chukchi Sea. It spans 13 degrees of latitude and extends more than 1,500 kilometers from Alaska (USA) to Russia (Figure 1). This large, dynamic ecosystem boasts some of the highest level of marine productivity in the world, supporting a US $1 billion commercial fishery and providing the U.S. with 50% of its wild-caught seafood (XXX). The Bering Sea is comprised of a deep-water basin, an extensive and highly productive eastern continental shelf, and a narrow western shelf (Fig. 1) (Stabeno et al. 1999). We restricted our analyses to the two continental shelves (depths < 200 meters (m)) because most NIS invade near-shore habitats (Ruiz et al. 2015). Only four NIS have been reported in the Bering Sea: *Alosa sapidissima*, *Caprella mutica*, *Mya arenaria*, and *Salmo salar* (Fofonoff et al. 2003; see Powers et al. (2006) for a discussion on the history of *M. arenaria* in Alaska). Of these, only *C. mutica* and *M. arenaria* have established populations (Ashton et al. 2008). Most vessel traffic in the Bering Sea comes from commercial vessels, specifically traffic from oil tankers

## Defining taxa-specific tolerances

As part of a larger risk assessment project (Reimer et al. 2017), we compiled temperature (T) and salinity (S) thresholds for NIS that currently occur in the Bering Sea, or in nearby marine ecoregions (*sensu* Spalding et al. 2007). The taxa list was developed by downloading and digitizing occurrence records from the National Exotic Marine and Estuarine Species Information System (NEMESIS; Fofonoff et al. 2003) and the Nonindigenous Aquatic Species Database (Fuller and Benson 2013). Given the time required for ranking, the list was subset to include only taxa that had been reported no further away than Washington-Oregon border in the east Pacific and the Sea of Japan to the west. Taxa were restricted to euhaline or euryhaline species with a minimum survival salinity tolerance ≥30 parts per trillion (ppt). The most common taxonomic groups were Crustacea (N=15), Mollusca (N=11), and Tunicata (N=8). Included in this list were two anadromous fish (*Alosa sapidissima* and *Salmo salar*), and one catadromous crab (*Eriocheir sinensis*). All taxa used at least one anthropogenic vector (e.g. ballast water, biofouling, intentional introductions) for transport (Reimer et al. 2017).

We found taxa-specific T-S survival tolerances for 42 NIS (Appendix A) and T-S reproductive tolerances for 29 NIS (Appendix B). We prioritized T-S thresholds from experimental or field-based studies, but used data inferred from geographic distribution when necessary because we considered this source of data to be superior to no data. Survival thresholds were intended to represent the broadest range of temperatures and salinities that a given taxon could tolerate. Survival thresholds were therefore defned as the absolute minimum and maximum values reported for that taxon, irrespective of life stage and geography. In contrast, establishment thresholds represent the narrowest T-S range required for growth or reproduction. If multiple thresholds were available (e.g. spawning versus larval development), we chose the thresholds associated with the least tolerant life stage.

Our models required information on minimum and maximum thresholds for both temperature and salinity. To maximize the number of taxa we could include in our models, we developed two additional criteria:

1. If the maximum temperature threshold was unknown, but survival had been observed in temperatures that exceeded the Bering Sea maximum (~17°C), we assigned an arbitrary maximum temperature value of +999 to ensure its inclusion in our analyses.
2. If salinity thresholds were unknown, but the taxon was a marine taxon that had been reported from ecoregions whose salinities were comparable to those of the Bering Sea, we set its salinity range to average seawater values (31 to 35 ppt), which would confer salinity survival to 98.8% of the Bering Sea shelf.

## Defining temperature and salinity of the Bering Sea

We compared taxa’s T-S thresholds to T-S values of the Bering Sea, which were obtained from three Regional Ocean Modeling Systems (ROMS) developed by NOAA's Pacific Marine Environmental Laboratory (PMEL) (Hermann et al. 2013, 2016). Each ROMS was generated by downscaling one of three general circulation model (GCM): 1) CGCM3-t47, 2) ECHO-G, and 3) MIROC3.2, which were chosen for their ability to accurately predict observed conditions in the Bering Sea and the northeastern Pacific (Wang et al. 2010, Hermann et al. 2016). ROMS outputs provide weekly values of temperature and salinity across the Bering Sea with a 6-nautical mile spatial resolution and for 10 vertical depth levels (Hermann et al. 2016). We restricted our analyses to depths up to 40 m, and summarized the depth dimension for each pixel into a single value by taking the maximum T-S values.

Projections were available for 37 years, from 2003 to 2039. We considered two 10-year study periods: current (2003-2012) and future (2030-2039) to explore potential changes in habitat suitability over time. Projections were based on the A1B emissions scenario from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Nakićenović et al. 2000). Compared to other scenarios, the A1B scenario implies moderate greenhouse forcing mitigation. However, because all scenarios generally track each other in the short-term, results from A1B GCMs do not differ substantially from other emission scenarios over the study period we considered (2003-2039; Nakićenović et al. 2000).

## Modeling habitat suitability

Our habitat suitability analyses consisted of three components: 1) year-round survival, 2) weekly survival, and 3) weekly reproduction. We developed suitability criteria for each of these components, but at its simplest, a taxon was considered to have suitable habitat if at least one pixel in our study area had T-S values that were within the taxon’s T-S thresholds. Habitat suitability was analyzed separately for each taxon, ROMS, and study period. Results were then summarized across taxa and averaged across all three ROMS. All analyses were conducted in R version 3.3.2 (R Core Team 2016) with support from the following packages: ddply, doSNOW, dplyr, ggplot2, ncdf4, maptools, plyr, rgdal, raster, rasterVis, rgeos, sp, viridis.

### Year-Round Survival

For each taxon, we defined a 6-nautical mile pixel as ‘suitable’ if the pixel’s T-S values remained within the taxon’s survival range for all weeks of a given year. We classified the pixel as ‘suitable year-round’ if it remained suitable for at least 7 years out of the 10-year study period. Cumulative suitability was then determined for each pixel by summing the number of taxa that had suitable year-round habitat in that pixel, and by averaging across the three ROMS. Lastly, we calculated the change in suitable area by dividing the sum of pixels with positive change by the total number of pixels in our study area. Percent decrease was similarly calculated.

### Weekly Survival

For each week, a taxon was considered to have suitable survival habitat if its T-S requirements were met in at least one pixel of the Bering Sea. Weekly survival was then calculated as the number of weeks per year identified as having suitable survival habitat, averaged across each 10-year study period. Unlike our year-round habitat analysis, where the same pixel had to remain suitable year-round, in this analysis we allowed suitable habitat to move in space from one week to the next. We summarized results across taxa by calculating the cumulative weekly averages for all 42 taxa; pixel values therefore represent 'average suitable week x number of taxa', with a theoretical maximum value of 2184 (52 weeks x 42 taxa).

### Reproduction Suitability

For each taxon, we defined a pixel as having suitable reproductive habitat if the T-S values for that pixel were within the taxon’s reproductive T-S thresholds for at least one week of a calendar year. For each year within our 10-year study periods, we calculated the number of consecutive weeks of suitable reproductive habitat, such that pixel values could range from 0 to 52. For our analysis, we used the maximum number of consecutive weeks within each 10-year study period as our metric; this value was calculated for each taxon and ROMS.

## Vessel traffic

We analyzed current vessel traffic and ballast water discharge in the Bering Sea using two datasets: the National Ballast Information Clearinghouse (NBIC) and Alaska’s Vessel Monitoring System (VMS). These data allowed us to quantify the magnitude and spatial pattern of traffic arriving at U.S. ports in the Bering Sea from fishing vessels and from large, commercial vessels (> 24 m). First-order port connections were examined using the circlize package (Gu 2014) in R Statistical Software version 3.3.2 (R Core Team 2016).

NBIC data are publicly available (https://invasions.si.edu/nbic/search.html) reports of vessel landings and their ballast water activities. Most large vessels (> 24 m) are required to report their ballast water exchanges when entering any port in the United States (33 CFR §§ 151). Because regulations have changed in the last decade, especially with respect to mandatory reporting by crude oil tankers (Verna and Harris 2016), we only considered the three most recent, complete years (2014-2016). We queried Ship Arrival Records and Ballast Tank Records from the NBIC data portal for any vessel arriving in Alaska from 01 January 2014 to 31 December 2016. Ports in Alaska were binned into one of the following regions: Arctic, Bering Sea / Aleutian Islands (BSAI), Gulf of Alaska (GOA), or Southeast Alaska (SEAK). Source ports with fewer than five trips reported were binned in a group labeled “Other”. Records without a port name were removed (*N*=13).

While the NBIC provides data on large, commercial vessels, it does not apply to smaller vessels ≤ 24 m long. Therefore, we relied on VMS data from Alaska to examine patterns of fishing vessel traffic. Current regulations by the National Marine Fisheries Service (NMFS) require VMS reporting by all fishing vessels that target walleye pollock, Pacific cod, Atka mackerel, and crab in the BSAI and the GOA (Spalding 2016). These locations are transmitted at 30-minute intervals. For consistency with the NBIC data, we examined all trips by vessels with VMS from 2014 – 2016, using methods from Watson and Haynie (2016). We analyzed a total of 4133 trips by 566 vessels during this time. Port connections with fewer than 3 different vessels were omitted according to confidentiality rules.

Some U.S. fishing vessels appeared in both the NBIC and the VMS databases, but are not easily queried because ‘Fishing’ is not a vessel type category in the NBIC database. To identify these records, we used their co-occurrence to create a ‘Fishing’ vessel type, thereby removing these vessels from the ‘Other’ category. These vessels were identified by linking NMFS fishing permit and U.S. Coast Guard numbers to the International Maritime Organization (IMO) vessel identifiers in the NBIC data via a NMFS vessel database (st.nmfs.noaa.gov/coast-guard-vessel-search/index).

# Results

Describe max/min water temperature threshold (minimum temperature thresholds ranged from -2C to …) talk about median? summer temps. . 1/3 of the taxa we considered had minimum temperature tolerances of 0C When averaged across the three ROMS, current (2003-2013) maximum water temperatures never exceeded 16.27°C (minimum: 3.77°C). By mid-century (2030-2039), water temperatures maximums are expected to increase by 2.34°C on average, with maximum temperatures in the Bering Sea projected to reach 18.62°C (minimum: 5.42°C) (see also Hermann et al. 2016).

## Year-round Survival

Of the 42 taxa we assessed, 34 were predicted to have suitable year-round conditions in at least one pixel in the Bering Sea (Figure 2). Our models predict that the southeastern Bering Sea, including the coastlines of the Aleutian Islands and most of the Alaska Peninsula, can support the highest number of NIS (Figure 2). The northern Bering Sea (above 58°N) is unsuitable for most NIS (Figure 2). By 2039, one additional NIS is expected to be able to survive year-round, and 76.6% of the Bering Sea shelf is predicted to switch from unsuitable to suitable for at least one NIS. In general, suitable habitat is expected to expand northward from the southeastern Bering Sea, as well as eastward into Bristol Bay (Figure 2). Only 7.5% of the modeled pixels are expected to switch from suitable to unsuitable habitat.

## Weekly Survival

\*\*Need to flesh out weekly results\*\* Of the taxa that cannot survive year-round, all have suitable habitat for at least six weeks during early July to mid-August (weeks 28 to 33; Figure 3). but for the most part habitat is unsuitable from December to early May (weeks 49 to 19), when temperatures in the upper water column fall below 1°C (Figure 3). Species with max salinity tolerances <=30ppt have little survival habitat.

## Reproduction

Reproductive tolerances were available for 29 NIS. Under current conditions, the Bering Sea continental shelf is predicted to support anywhere from 0 to 20 taxa (median=7.33 taxa per pixel). Most areas of high NIS richness are in the southern Bering Sea, and include the Aleutian Islands, the Alaska Peninsula, the Commander Islands, and the Kamchatka Peninsula. Maximum NIS richness is also predicted along the southern Seward Peninsula and in Norton Sound (64°N; Supplementary Figure 1). Taxa that can reproduce in marine salinities (≥31 ppt) at 4°C had nearly year-round suitable reproductive habitat (Figure 4). However, number of consecutive weeks of suitable habitat declined exponentially with temperature thresholds (Figure 4). Marine taxa that required minimum temperatures of 12°C had fewer than six consecutive weeks, and species requiring minimum temperatures >14°C had less than one week (when averaged across models; Figure 4). Five taxa had no suitable habitat anywhere on the Bering Sea shelf (Figure 4).

By 2039, the maximum number of taxa that can reproduce in the Bering Sea is expected to increase by one, and suitable habitat is expected to increase across taxa (median=8.33 taxa per pixel). The number of weeks suitable for reproduction is also expected to increase (Figure 4), though taxa with minimum reproductive thresholds ≥14°C are still predicted to have less than 2.5 weeks of suitable temperatures (Figure 4).

## Vessel traffic

The NBIC data reported a total of 816 arrival records and 15,837 ballast water discharge reports in U.S. Bering Sea ports[[1]](#footnote-1) from 2014 to 2016. Records were distributed across 9 vessel types: Bulker (*N*=2755), Container (*N*=295), General Cargo (*N*=114), Other (*N*=396), Passenger (*N*=774), Refrigerated Cargo (*N* = 418), Roll-on/Roll-off Cargo (*N* = 10), Tanker (*N*=9935), and Fishing (*N*=1140). Dutch Harbor received the greatest amount of traffic for both NBIC and VMS reported boats (Figure 5). Nome received the second highest amount of traffic for NBIC reported vessels, and Akutan received the second highest amount of traffic for VMS reported vessels. With respect to ballast water discharge, the majority of reported discharge occurred in Dutch Harbor, with Nome having the second largest discharge volume (Supplementary Figure 2).

82.7% of arrivals (of NBIC ships?) originated from outside Alaska (Figure 5a). According to the NBIC dataset, California (*N*=175), Washington (*N*=142), and South Korea (*N*=127) accounted for greater portions of vessel traffic into the Bering Sea than the more proximate Gulf of Alaska ports (*N*=120). However, from VMS data, which predominantly includes smaller fishing vessels that do not report to the USCG, an overwhelming majority of trips originated from Gulf of Alaska ports (*N*=657; Figure 5b). While ports in the eastern Pacific Ocean accounted for more trips, most ballast water released in the Bering Sea originated from Asian ports (Supplementary Figure 2). South Korea and China each accounted for an order of magnitude more ballast water (18,728 and 17,453 mt, respectively) than the next greatest sources, Japan (7183 mt), Canada (6912 mt), and Washington (3852 mt). Approximately 20% of the 15,837 ballast water exchange records (representing 10.6% of the discharged volume) identified the source of their ballast water using coordinates (typically from offshore waters) instead of port names. Among these non-port ballast water sources, 25% of water originated from locations in the northeast Pacific Ocean (defined here as latitudes > 23.5° N, longitudes between 179.9° W and 110°W) and 15% originated from locations in the northwest Pacific Ocean (defined here as latitudes > 23.5° N, longitudes between 100° E and 180° E).

# Discussion

Although the Pacific Arctic has few reported non-indigenous species (NIS), our results indicate that (1) potential NIS habitat currently exists in the Bering Sea; (2) this potential NIS habitat is projected to expand by mid-century due to warming ocean conditions; and (3) mechanisms for NIS propagule transport into and throughout the Bering Sea exist and may well increase. These results challenge the expectation that high-latitude marine ecosystems have low risk due to temperature limitations on habitat. [..]

Our results suggest that species’ tolerance to cold water temperatures limit their invasion potential in arctic regions; however, subarctic regions that are perennially ice-free are suitable for a large number of temperate taxa. We identified suitable temperature and salinity conditions for both survival and reproductive life stages… Importantly, areas of high habitat suitability were also areas that received the highest number of commercial and fishing vessels. Collectively these results suggest that…. Areas of high vessel traffic intersect with areas of high habitat suitability, which is cause for concern.

## The role of cold water temperature on survival

Of the 42 taxa we considered, most (*N*=34) had suitable habitat for year-round survival in at least parts of the Bering Sea. NIS richness followed a strong, latitudinal gradient, with high richness in the southern Bering Sea shelf, and a sharp decrease above 58ºN (Figure 2). This gradient is coincident with the limit of seasonal sea ice extent in the Bering Sea (Grebmeier et al. 2006b, Stabeno et al. 2012). Seasonal sea ice cover in the southern Bering Sea is either entirely absent (e.g. the Aleutian Islands), or strongly variable from one year to the next (Stabeno et al. 2012). Meanwhile, the northern Bering Sea is more similar to arctic ecosystems, both in terms of its hydrology and its species assemblage, and its seasonal dynamics are driven, to a large extent, by the presence, timing, and extent of sea ice (Grebmeier et al. 2006a, Mueter and Litzow 2008). de Rivera et al. (2011), who developed ecological niche models to predict the distribution of four potentially invasive species in Alaska, three of which we consider here. Our models support their main finding that current environmental conditions in high-latitude systems do not preclude survival (de Rivera et al. 2011), but by considering a larger number of taxa, we found that most species do not have the ability to live up to the Arctic… (Figure 2). [[briefly talk about importance of seasonality – winter]]: Of the 42 taxa we considered, all were predicted to survive in some of the Bering Sea for at least six weeks of the year, when water temperatures were warmest (from early July to mid-August). Taxa without year-round survival habitat were unable to survive during the coldest months of the year (from December to April).

## Reproduction: Is there enough time?

Very few studies have modeled potential reproductive habitat in the Arctic, despite the potential for cold temperatures to affect larval survival, development, and recruitment (de Rivera et al. 2007.. need more) We found that most taxa we evaluated had at least one week of suitable reproductive habitat. In contrast to our year-round survival model, which showed declining NIS richness with latitude, the very shallow waters of Norton Sound (~64°C) are a thermal hotspot in the Bering Sea (Ladd and Overland 2009, Hermann et al. 2016), and were therefore predicted to support the greatest number of NIS during the summer months. However, taxa that require salinities ≤30 ppt or temperatures ≥14°C for reproduction or development, have limited suitable habitat in the Bering Sea. Given the link between temperature and time to development (e.g. de Rivera et al. 2007), taxa with long brooding or development periods may be limited by the Bering Sea’s short summer season. For example, prominent invaders such as *Botrylloides violaceus* and *Carcinus maenas* either do not have suitable temperatures or do not have enough time to complete development, despite having the capacity to live year-round across moderately large areas of the shelf (de Rivera et al. 2007, Westerman et al. 2009). Interestingly, the two NIS that are established in the Bering Sea (*Caprella mutica* and *Mya arenaria*)were the two outliers in our dataset that had nearly year-round reproductive habitat (>51 consecutive weeks of suitable repro habitats).

Given the resolution of the climate models we used, our habitat models may underestimate summer water temperatures near the coastlines and in shallow waters < 10 m deep. In addition, the ROMS we used do not account for the influence of rivers of ocean temperatures (the effect on salinity is included, though estimates are coarse). The influence of rivers is significant in our study area given the many large rivers that drain into the Bering Sea (e.g. Yukon, Kuskokwim, Nushagak..). These rivers not only contribute to freshening the Bering Sea, but also increase near-shore water temperatures by several degrees in the summer. Measurements from finer scale models have recorded temperatures as high as 19°C near the Yukon River. Local dynamics such as freshwater runoff and ice scour is likely to affect species’ distribution and persistence (Fetzer and Arntz 2008, Miller 2016). However… results for year-round survival still supported …

Our approach, which uses physiological tolerances rather than environmental matching, is especially meaningful in systems such as the Arctic, where environmental conditions fall outside the range of values to which taxa are exposed in their current range (Miller 2016). Nevertheless, there is a lack of knowledge on the physiological thresholds of most marine organisms, especially with regards to critical lower limits and phenotypic plasticity (Sorte et al. 2011, Huang et al. 2017). More experimental research is needed to determine development rates of NIS under different temperature conditions, and examine the various facets of reproduction, as asexual reproduction, fertilization, brooding, and development stages may all require different temperature thresholds (Westerman et al. 2009). Future modeling efforts need to consider variables beyond water temperature and salinity. An organism’s body temperature may be affected by factors beyond water temperature (e.g. wind for intertidal organisms; Monaco and Helmuth 2011), and its survival or reproductive success is influenced by several other factors, including competition, food availability, and water chemistry (Valdez and Ruesink 2017). The potential for interactions and non-linear responses may also be especially important at the tail-end of species’ thermal response curves (Monaco and Helmuth 2011, Sorte 2014, Miller 2016).

## Vessel traffic

Both commercial and fishing vessel traffic, and ballast water discharge point to the port of Dutch Harbor as being by far the most visited port in the Bering Sea region. Vessel traffic patterns also indicate a high degree of connectivity between Dutch Harbor and ports from both the eastern and western Pacific Ocean. Trips ending in Dutch Harbor originated from more than ten countries from around the world. The connectivity of Dutch Harbor to other Bering Sea ports, like those of the Pribilof Islands, Bristol Bay, and Akutan, emphasizes the scale of connectivity among many Alaskan communities and further underscores the potential impacts of invasive species in Dutch Harbor. Without a road system to provide access to Alaska’s port communities, vessels of all types form a marine highway system that is traveled by ferries, tugs, barges, and as demonstrated here, fishing vessels. Many of these vessels are not required to report ballast water activities because of their size or because they remain within State waters. We extend work by McGee et al. (2006) by quantifying the fishing vessel traffic in the region. While these boats do not carry ballast water, they may be important vectors of biofouling. Organisms such as barnacles, copepods, and algae can be transported via fouling; while much attention has been placed on ballast water, a study in the Canadian Arctic found a greater abundance and richness of hull foulers compared to ballast water organisms, suggesting that biofouling may be a greater contributor to introductions than ballast water (Chan et al. 2015). Future analyses of vessel traffic in the context of invasive species transport may benefit from analysis of Automatic Identification System (AIS) data, which are available for a greater portion of vessels traveling through Alaskan waters.

We assumed that high-traffic ports are more susceptible to receiving NIS than low-traffic ports, and that shipping traffic and ballast water discharge are adequate proxies of propagule pressure. previous studies indicate that shipping traffic is correlated to NIS richness (e.g. Lord et al. 2015; Lacoursière-Roussel et al. 2016), and ballast water discharge volume has been shown to be ?? (see Verna et al. 2016..). While these simplifying assumptions were necessary considering the data that were available to us, we recognize that an organism’s survival during a sea voyage is influenced by several factors including its physiological condition, the voyage duration, and environmental differences between donor and recipient ports (Carlton 1996, Verling et al. 2005, Chan et al. 2014). Propagule pressure and conditions encountered during the voyage may play a greater role than conditions encountered upon arrival. Historically low propagule pressure (pre-1970) is potentially a large explanation for lack of invasions in coastal Alaska, and may be a more important component of invasion risk than environmental conditions at recipient ports (Ruiz et al. 2000). Conditions encountered during the voyage may also play a role. Studies from the Canadian Arctic suggest that both planktonic and fouling organisms have low survivorship during the transport stage (Chan et al. 2014, 2016). Chan et al. (2014) found that ballast water age (related to the length of the voyage) was a more important predictor of survivorship than water temperature, and suggested that voyages longer than 15 days may significantly reduce survival probability. Verna et al. (2016) quantified ballast water risk of Alaskan ports and found that while Dutch Harbor was at medium risk in terms of discharged water volumes, the relatively long residence time of the ballast water that was discharged there was likely to reduce the probability of establishment.

## Effects of climate change on invasion risk

The Bering Sea is experiencing significant oceanographic changes as a result of climate change (e.g. Grebmeier et al. 2006b, Stabeno et al. 2007, Mueter and Litzow 2008). Sea ice cover has decreased substantially since the 1950s, with a concomitant increase in surface water temperatures of 0.23°C per decade (Mueter and Litzow 2008). These changes are projected to continue (Wang et al. 2012, Hermann et al. 2016). In the next twenty years, our models predict a major northward expansion in suitable habitat (Figure 2) that would largely favour taxa that already have the capacity to survive in the southern Bering Sea. Contextualize degree change in temp. with % change in suitable habitat. Northward range shifts in the Pacific Arctic have already been documented for native fish, zooplankton, and benthic invertebrates (e.g. Grebmeier et al. 2006b, Matsuno et al. 2011, Stabeno et al. 2012, Kotwicki and Lauth 2013), and the few studies modeling Arctic invasions have also documented a poleward expansion of suitable habitat in the future (Goldsmit, Ware). The role of temperature as a limiting factor in northern Europe was shown for Crepidula fornicata

Several studies have suggested that NIS can persist at a low population size for years and suddenly undergo a boom when conditions become favourable (Witte et al. 2010). In temperate systems, warming ocean temperatures affect the survival (Groner?), growth rates, reproductive output, and phenology of NIS (Stachowicz et al. 2002, Saunders and Metaxas 2007, Valdizan et al. 2011, Lord 2017). ((future climate change)) Warmer winter water temperatures have been linked to the earlier onset of recruitment and increased recruitment of NIS We did not consider possible interactions between temperature, salinity, and water chemistry, and these might be especially important in the context of climate change as melting sea ice in the north is expected?? To lower salinities, and ocean acidification is lowering pH and causing problems for calcareous?? Organisms.

The suitable temperature conditions of the southern Bering Sea are especially concerning considering the high vessel traffic in the region. The Bering Sea is the only waterbody that is included in both NSR and northwest passage. It receives nearly 50% of all traffic in the Arctic region, and an additional 600 to 900 vessels are expected to navigate the Bering Sea by 2025 (Ellis and Brigham 2009). Future expansions of the Arctic for shipping and oil and gas exploration may lead to continued development of plans for establishing industrial scale port facilities in northern ports such as Nome, which currently receives little traffic. Our current models emphasize southeastern Bering Sea… highly suitable temperatures across a large number of taxa.. home to largest U.S. fishery port….. and economic driver of Alaska… Situated at 53.9°N, this port is one of the most southerly ports in the Bering Sea, is ice-free year-round, and experiences relatively warm water temperatures compared to the rest of the Bering Sea. Broader implication = monitoring program.

A study in the contiguous U.S. found that temperature and cargo shipping traffic explained 53% of the variation in non-native species richness in marinas (Lord et al. 2015).

potential papers to cite:

The risk of nonindigenous species invasion in Prince William Sound associated with oil tanker traffic and ballast water management : pilot study / presented to Regional Citzens' Advisory Council of Prince William Sound ; presented by Gregory M. Ruiz and Anson H. Hines.

# Acknowledgements

Funding for this project was made available by the North Pacific Research Board (project #1532) and the Aleutian and Bering Sea Islands Landscape Conservation Cooperative. Tracey Gotthardt and Aaron Poe were involved with spearheading the project. Casey Greenstein, Lindsey Flagstad, Bonnie Bernard, Jaime Weltfelt, and Curtis Whisman contributed to the development of the ranking system and the species status reports. Additional thanks goes to Matt Carlson for initial feedback on this manuscript. J.W. thanks Jen Karnak of Marine Exchange of Alaska, who assisted with vessel identification. A.F. thanks Rob Bochenek and Dr. William Koeppen of Axiom Data Science for assistance extracting the ROMS data. A.D. thanks Marcus Geist for his GIS wizarding, and Al Hermann for insightful conversations about the ROMS.

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Table 2. Average number of weeks of consecutive reproductive habitat for the three ROMS models and two study periods. We assessed suitable habitat for 29 species using species-specific, published temperature and salinity thresholds required for growth and reproduction. Prior to calculations, we excluded species that could not reproduce in our study area (number of weeks = 0) and two “outliers” that were able to reproduce nearly year-round (number of weeks ≥ 49). Maximum projected temperature values for the Bering Sea, up to 40m depth, are listed.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Study Period** | **Model** | **Consecutive weeks** (mean ± SD) | **Number of species** | **Maximum temperature** (°C) |
| Current  (2003-2013) | CGCM3-t47 | 9.19 ± 8.19 | 21 | 16.26 |
| ECHO-G | 5.60 ± 6.90 | 22 | 16.95 |
| MIROC3.2 | 6.72 ± 6.36 | 20 | 16.28 |
| Future  (2030-2039) | CGCM3-t47 | 9.40 ± 9.31 | 23 | 16.64 |
| ECHO-G | 6.21 ± 7.02 | 22 | 17.15 |
| MIROC3.2 | 8.53 ± 6.94 | 24 | 18.62 |

**Figures**

Note: Figures 1 and 2 should have all (or some?) Bering Sea ports on the maps to help readers place the network plot results from Jordan’s figure. If it’s too cluttered, we can create a simple reference map to go along with the network plots.

Figure 1: Study area map with all place names and U.S. ports.

Figure 2. **Ensemble mean for year-round survival.** Number of species with year-round habitat suitability under a) current (2003-2012) and b) future (2030-2039) climate conditions, averaged across the 3 ROMS we analysed (CGCM3-t47, ECHO-G, and MIROC 3.2).

Figure 3. **Number of taxa with survival as a function of latitude + weeks (heat map).**

Figure 4. **Average number of consecutive weeks of reproduction by temperature threshold**. Based on taxa tolerances, averaged across models or separate out? Current is probably most interesting & I don’t think things change drastically?? With future but should double-check. See below for an example.

Figure 6. Commercial + fishing vessel chord diagrams (2 figures).

Supplementary:

-ballast water discharge



Figure 5. **Average number of consecutive weeks of reproduction by temperature threshold**.



Figure newX2. Illustration of vessel transit origins (below dashed line) outside of the Bering Sea and their Bering Sea destination (bold text, above dashed line), 2014 - 2016. Numbers in parentheses indicate numbers of records for a given port. (Top) Data from arrival records in the National Ballast Information Clearinghouse. “Other” includes ports with ≤ 5 transits. (Bottom) Fishing vessel data from vessel monitoring systems. Connections with fewer than three vessels have been excluded to retain confidentiality.



Figure XXBallast. Amounts of ballast water (mt) transported to the Bering Sea (bolded ports, above dashed line) and their regions of origin (unbolded text, below dashed line). Numbers in parentheses show total volumes per region. Figure excludes ballast water exchanges not reported by a specific port / country (e.g., open ocean exchanges), totaling ~80% of reported ballast water exchange. Data from the National Ballast Information Clearinghouse.

1. Discharge reports that did not include valid source locations were omitted from the analyses. [↑](#footnote-ref-1)