

# Aliens in the Antarctic Ocean:

## Invasion risk assessment of the Antarctic marine ecosystem

E. Abdullah | Supervised by A.G.J. Buma

### Abstract

The Antarctic Ocean is characterised by extreme temperatures and high seasonal variability. This has allowed only the most adapted species to survive and populate the benthic communities, resulting in a high rate of endemism. Due to a lack of shell-crushing (durophagous) predators, the Antarctic Ocean communities are dominated by invertebrates, displaying high levels of diversity which would not be assumed based on the external conditions. However, due to elevated sea surface temperatures, increased light incidence levels and increased vessel transport into the Antarctic Ocean, these pristine and sensitive communities are now being threatened by several threats, including invasive species. Novel introductions of durophagous predators may disrupt the current marine ecosystem, altering its function or even causing desertification. Invasive invertebrates may outcompete the endemic species and decrease diversity, lowering the stability of the Antarctic system. The main transport across the Antarctic ocean for non-endemic species is by anthropogenic vessel transport, either by attaching to the hulls of ships or finding refuge in ballast water or sea chests. Therefore, prevention of alien species should focus on the inspection of ships into the Antarctic Ocean, especially those that frequent higher latitude waters including the Arctic, since these species already possess adaptations to protect them from the extreme cold in the Antarctic Ocean. While currently there have not been any reproductive populations established in the Antarctic Ocean, several durophagous and invertebrate species are poised to invade due to increases in global temperatures and should be monitored closely.

# Table of Contents

<b>Abstract.....</b>	<b>1</b>
<b>Table of Contents.....</b>	<b>2</b>
<b>Introduction .....</b>	<b>3</b>
<b>Current Benthic Ecosystem.....</b>	<b>3</b>
<b>Adaptations to the cold.....</b>	<b>4</b>
<b>Invasion-limiting conditions .....</b>	<b>5</b>
<b>Warming events.....</b>	<b>6</b>
<b>Ocean Acidification .....</b>	<b>7</b>
<b>Current invasive threats .....</b>	<b>9</b>
<b>Guideline and Policies .....</b>	<b>14</b>
<b>Further investigation.....</b>	<b>14</b>
<b>Conclusion .....</b>	<b>14</b>
<b>References.....</b>	<b>15</b>

## Introduction

The Antarctic marine ecosystem is characterized by its unique combination of stable cold temperatures and highly variable light and food availability (Peck et al 2014; Power, 2018; Morley et al., 2009). These factors are mainly attributed to the Antarctic Circumpolar Current (ACC), an ocean current which isolates the cold southern waters from the more temperate northern waters (Aronson et al., 2007). This, in combination with the polar front (PF), a wind-driven boundary which separates the Polar and Ferrel wind cells, has resulted in a barrier for marine species which historically has caused the Antarctic Ocean to be isolated for many millennia (Aronson et al., 2015; Morley et al., 2009). Antarctic marine benthic species have adapted to the cold climate via various different pathways, including a lowered metabolism, gigantism and antifreeze mechanisms (Aronson et al., 2007). In addition to this, the invertebrate communities have been free of predation. In lower latitudes, predation pressure on invertebrates is predominantly inflicted by durophagous (hard-shell eating) predators (Aronson et al., 2007). In the Antarctic Ocean however, no durophagous predators have been able to settle due to a lack of sufficient down-regulation of magnesium ions in their haemolymph at cold temperatures, severely limiting their ability to function (Wittman et al., 2010; Aronson et al., 2015; Barnhart, 2001). These factors have contributed to the unique marine ecosystem in the Antarctic Ocean, resulting an archaic community structure (Aronson et al., 2007). Research has also indicated that, since the Antarctic marine community is subject to stable temperatures, their resulting heat-tolerance gradient is extremely narrow. Isolation and stable temperature conditions have moulded the current-day Antarctic benthic community for

millennia (Power, 2018; Aronson et al., 2015; Morley et al., 2009), however in light of recent anthropogenic induced climate change, in addition to increased vessel activity into the Antarctic waters (Bender et al., 2016), these pristine ecosystems are presently threatened. In order to assess the Antarctic marine ecosystem, this review aims to answer the following question: What are the current and future risks posed to the Antarctic marine ecosystem by invasive species in a changing world? Anthropogenic causes and alternate risk factors will be discussed, as well as different pathways for invasion by alien species and their effects on the current ecosystem. To highlight the potential effects of invasions, two key invasive taxa will be considered; durophagous crabs and competitive invertebrates. To create accurate guideline and policies for reduction of future invasion events, scenarios under global surface warming and ocean acidification will be explored.

## Current Benthic Ecosystem

Presently, the Antarctic marine benthos is dominated by filter-feeding sessile invertebrates (Hellberg et al., 2019; Aronson et al., 2007). Absent in these communities are the durophagous (shell-eating) predators. These predators include certain fish, decapods, crabs, lobsters, sharks and rays. Durophagous predators are even seen in the Arctic, namely walruses and grey whales (Aronson et al., 2007) In these areas, the durophagous predators inflict heavy top-down regulation on the invertebrate communities (Hellberg et al., 2019; Innes, 2016). Without these predators, high amounts of diversification is seen, more than would be expected based on physiological parameters. A high level of endemism is also characteristic for the Antarctic Ocean (Power,

2018; Peck, 2018) since the ACC and polar front create a tight barrier, preventing the influx of species from other ocean currents. This isolation has caused the Antarctic benthic community to share similarities with archaic and deep-sea communities (Aronson et al., 2007). This is further enforced by the sharp gradient in depth of the Antarctic shelf, which historically may have allowed deep-sea species to migrate and adapt to a benthic lifestyle (Aronson et al., 2007). While temperature conditions in the Antarctic Ocean are stable, they are the coldest on earth. Light and nutrient availability is extremely variable, resulting in a short feeding period of two months (Barnes & Clarke, 1995). This has implications for marine life, many of which show low rates of metabolism and low levels of activity. It also explains the predominantly sessile way of life in the benthic community. These communities are regularly subjected to high rates of mortality due to ice scouring, a phenomenon where the keel of moving ice gauges the seabed (Barnes, 2017; Barnes et al., 2014). This can result in communities being kept at early succession stages or even cause local extinctions (Figure 1) (Peck et al., 1999; Barnes et al., 2014; Barnes et al., 2011). This may also contribute to the high diversification

rate, where ice scouring keeps fast-growing r-strategists in check and prevents them from dominating communities (Peck et al., 1999; Barnes et al., 2014).

### Adaptations to the cold

The Antarctic Ocean displays one of the highest levels of diversity, combined with a high rate of endemism. (Peck, 2018). While the ACC and PF pose physical barriers, they do not completely exclude cross-oceanic transport of species. However, the cold sea-surface temperatures pose a physiological barrier which has proven to be difficult to cross, represented by the extremely low amount of reproductive populations of invasive species (Turon et al., 2016). The main reason for the inhabitation of pervasive durophagous communities is the limited ability to down-regulate magnesium ions in the haemolymph at colder temperatures (Hellberg et al., 2019; Aronson et al., 2015). This limitation causes a paralytic reaction at low temperatures, making survival near-impossible in the Antarctic Ocean (Aronson et al., 2015). Most Antarctic invertebrates have adaptations which allow them to down-regulate magnesium ions, allowing them to maintain motor functions in sub-zero living temperatures (Wittmann et al., 2010). Certain non-durophagous crustaceans like Caridean shrimp are able to regulate their magnesium levels, attributing to their presence in the Antarctic Ocean (Wittman et al., 2010; Barnhart, 2001). Interestingly, Antarctic isopods show rates of magnesium down-regulations similar to those found in temperate species (Figure 2) (Aronson et al., 2015) and must therefore have different mechanics to maintain motor-functioning in cold conditions.

While down-regulation of magnesium allows for species to retain their functioning, low

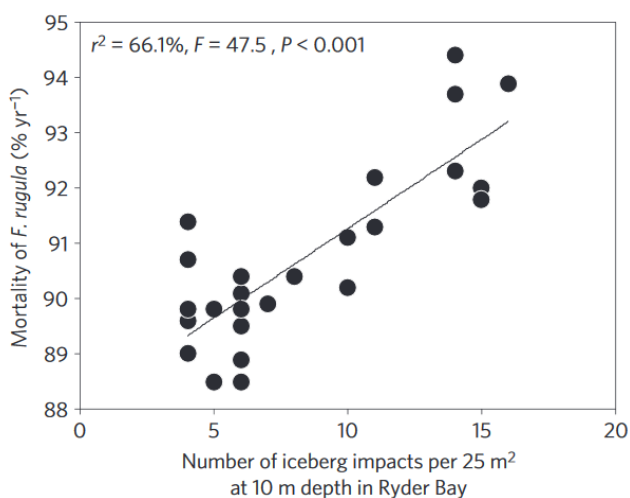


Figure 1: Mortality rate of *F. Rugula* against the number of iceberg impacts. Increased ice scouring events cause increases in mortality rates. (Barnes et al., 2011)

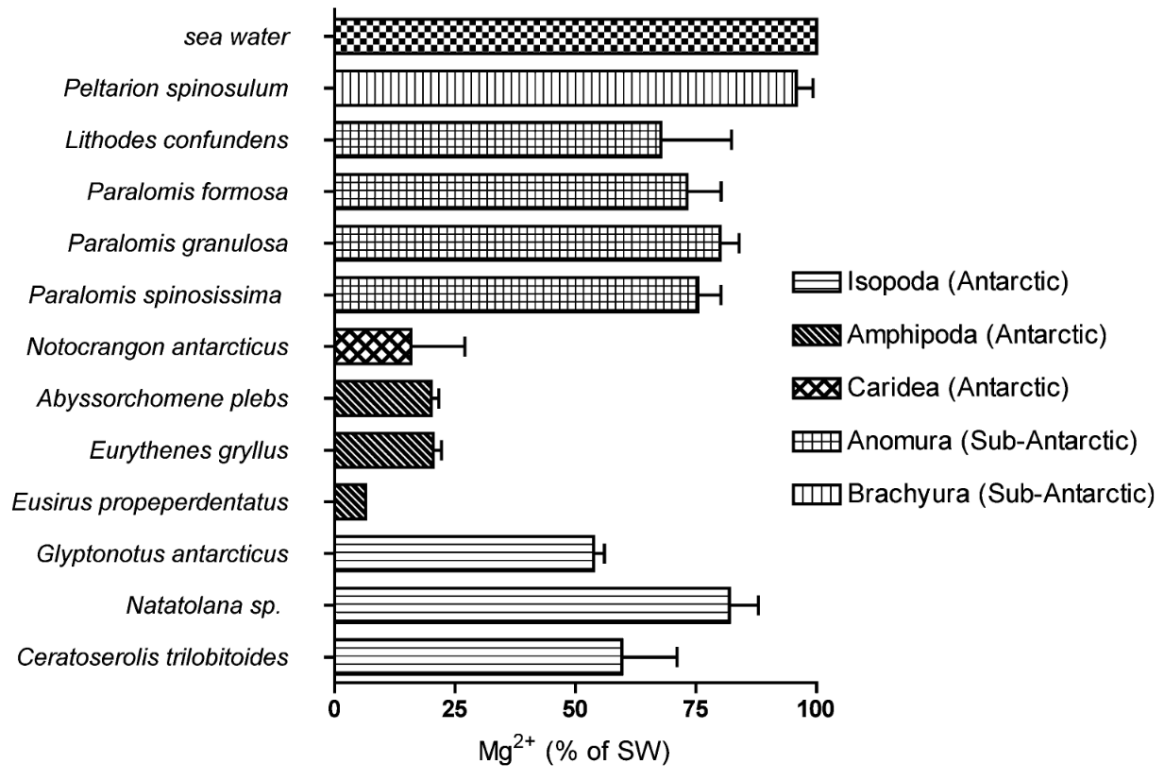


Figure 2. Concentration of magnesium ions in the haemolymph of Antarctic and Sub-Antarctic crustaceans. Antarctic species show low values of magnesium in their haemolymph except for the isopods, who show levels similar to sub-Antarctic

activity is a key characteristic of cold-adapted species. By lowering their metabolism, marine species can operate more efficiently, reducing oxygen consumption and thus allowing for increased optimization in the cold (Aronson et al., 2007). To further increase efficiency, gigantism, which is characteristic of deep-sea habitats, is also seen in the benthic communities. Turn-over rates in the Antarctic Ocean are considerably low when compared to temperate species due to slow growth and slow rates of reproduction resulting in long generation times (Peck et al., 2014). For Antarctic species, physiological rates are measured to be near ten-fold slower than species living in 10 degree higher sea-surface temperatures (Peck, 2016). While their slow lifestyle is an efficient adaptation to the cold environment, it results in long recovery times, should these communities be threatened. This makes the Antarctic benthic ecosystem vulnerable to changes and increases its sensitivity to biotic and abiotic threats.

Furthermore, adaptations to the stable conditions of the Antarctic Ocean has caused the benthic community to become stenothermal (peck et al, 2014; Power, 2018; Clarke et al., 2007; Morley et al., 2009), a state where tolerance to temperature variation is considerably low. This is attributed to problems in the protein folding process, increasing heat shock proteins which heightens sensitivity to thermal changes (Peck, 2016). For certain species, this means that a 1°C warming can cause inhabitable conditions and may result in numerous extinction events (Power, 2018).

#### Invasion-limiting conditions

One of the key threats to the current Antarctic benthic community is the potential of invasive species. Several species have already been found invading the Antarctic Ocean, however only few are able to

maintain stable reproducing populations. In addition to the ACC and PF barriers, the cold conditions cause a tough boundary for invasions. Magnesium regulation problems inhibit motor functions of most durophagous predators but there are certain species which show down-regulation levels which would allow them to invade the Southern Ocean. While this may be true, the cold conditions provide another constraining factor by decreasing the power output of muscles, requiring up to 10 fold more effort to crack through invertebrate calcite shells (Aronson et al., 2007). However, since the shells of most invertebrates are softer than their temperate counterparts, in addition to the lack of predatory pressure to form appropriate defences, the effects of predation by durophagous predators on the invertebrate community remains largely ambiguous. One of the advantages durophagous predators have over other species is that Antarctic marine communities are dominated by their prey, calcified invertebrates. This large food reserve would allow them to proliferate rapidly, should they bypass the other inhibiting conditions. Invertebrate invasive species will find the opposite to be true. Due to the high variability in light incidence and seasonal sea-ice extent, feeding periods are notably short, lasting up to two months (Clarke et al., 2007). The adaptations of the endemic invertebrates allow them to efficiently take up nutrients from the water column, up to the level of nanoplankton (Barnes & Clarke, 1995). Their slow way of life also increases their efficiency with the nutrients that they are able to take up.

### **Warming events**

Historically, the Antarctic Ocean has been physically and physiologically isolated from

the rest of the world. However, due to present day global change, the stability and isolation of this system is at risk. Evidence has shown that global warming has increased sea-surface temperatures across the globe. The southern Ocean has been at the forefront of this warming, measuring the highest recorded warming trends in the Western Antarctic Peninsula (Meredith & King, 2005). This is decreasing the effectiveness of the near-impermeable physiological cold barrier, increasing the risk for invasive species, as well as posing a direct threat to the stenothermal endemic species. By measuring diversity in certain genetic markers, studies of prehistoric warming events have inferred the presence of durophagous predators in the southern Ocean to coincide with natural rapid warming events (Hellberg et al., 2019). Anthropogenic climate change is predicted to have similar effects, increasing southern Ocean temperatures, thus allowing species with poor magnesium ion down-regulation to achieve stable reproducing populations. Ocean warming poses threats to many marine species. At-risk species will have different pathways of dealing with the rapid warming (Griffiths et al., 2017):

- 1 acclimate
- 2 adapt
- 3 migrate
- 4 go extinct

Species with a high turn-over rate can adapt rapidly to the changing environment, allowing them to survive future warming events with ease. Many species who can't adapt fast enough will migrate to higher latitudes to counteract the effects of change. Sub-Antarctic species could migrate southward in an attempt to mitigate the effects of ocean warming and maintain their habitats (Griffiths et al., 2017). However, Antarctic benthic species are at the highest inhabitable

latitudes, making migration impossible (Power, 2018; Griffiths et al., 2017). The stability of temperatures in the Southern Ocean further limits the effectiveness of migrating to a more suitable habitat. Adaptation will also be an issue because of the low turn-over rate due to the low growth and production rates. This forces them to either acclimate or to go extinct. Acclimatisation in the Southern Ocean ecosystem has been investigated and it is found that southern oceanic species either do not acclimate or acclimate very slowly, taking up to four times longer than temperate-adapted species (Figure 3). These acclimatisation rates show similarities with tropical species which similarly inhabit temperature-stable waters (Peck et al., 2014; Power, 2018; Morley et al., 2009). This indicates that stability of habitat temperature may influence the ability of species to manage changes in sea-surface warming.

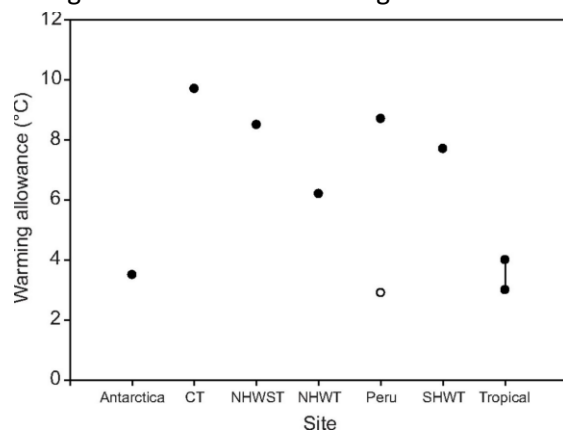


Figure 3. Warming allowance (in °C) from aggregates of species from the Antarctic to the tropics. Warming allowance is calculated as the difference between the species' maximum thermal tolerance and the maximum environmental temperature they are currently found in. The white dot depicts an El Niño event (Adapted from Peck et al., 2014).

The Antarctic Peninsula is currently the fastest warming area on Earth (Meredith & King, 2005). Feedback mechanisms, driven by increased atmospheric CO<sub>2</sub>, are predicted to further increase warming rates in the Southern Ocean. Increased temperatures are

causing faster sea ice retreat, resulting in a lowered albedo, increasing temperature levels even faster (Clarke et al., 2007; Cook et al., 2010; Meredith & King, 2005). This may increase the production rates of primary producers and lengthen the short feeding period in the Antarctic Ocean. The benthic community which has been adapted to predictable food supply opportunities are especially sensitive to changes in the duration and timing of nutrient availability (Clark et al., 2013; Meredith & King, 2005). Evidence shows that, should ice loss occur to a significant extent, the current invertebrate-dominated system of the benthic community might shift towards an algae-dominated system (Figure 4). This threatens the endemic diversity and may alter the services that this ecosystem provides (Clark et al., 2013).

### Ocean Acidification

Anthropogenic effects have caused global temperature increases by increased CO<sub>2</sub> levels. These increased CO<sub>2</sub> levels are also a cause for lowered pH in oceans, causing ocean acidification. A decreased oceanic pH is of great consequence to calcifying organisms, since they require CaCO<sub>3</sub> for their shells (McClintock et al., 2009). Antarctic calcifying invertebrates have weaker calcified shells than those at lower latitudes. This is presumably a combination of lack of durophagous predatory pressure removing the need for hardened defensive structures, and the increased difficulty of extracting CaCO<sub>3</sub> in colder temperatures (McClintock et

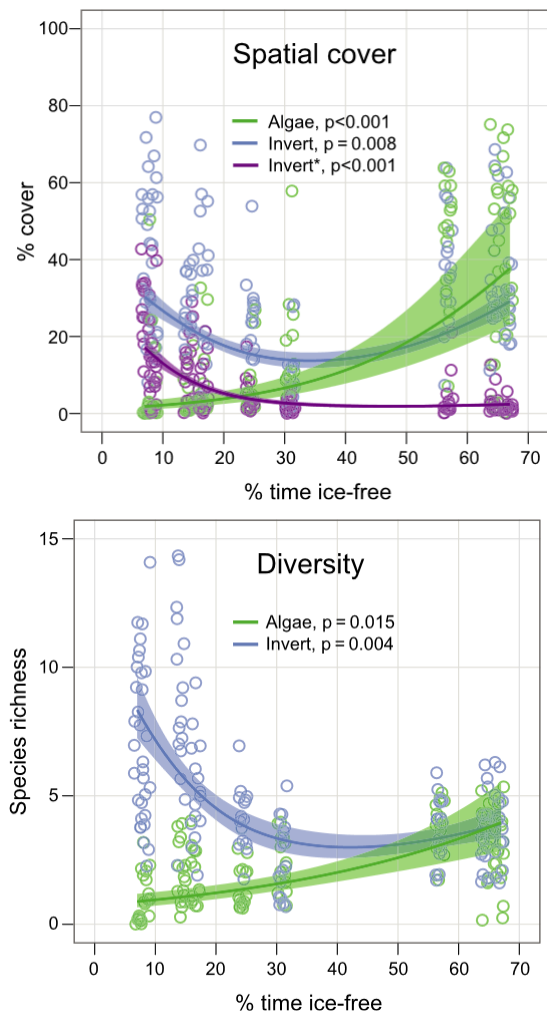


Figure 4. Top: coverage (%) of taxa plotted against increased duration of ice-free periods (% of total time). Long ice-free periods result in increased light availability, favouring algae dominated systems. Bottom: species richness against duration of ice-free periods. Algae-dominated systems result in a decreased diversity when compared to invertebrate-dominated systems (Clark et al., 2013).

al., 2009; Watson et al., 2017; Watson et al., 2012). Ocean acidification further increases the cost of shell-production, with predicted acidification scenarios showing cracks in the calcified shells within 2 months (Figure 5, 6). Acidification and increased temperatures due to global change pose significant threats to the already vulnerable calcifying invertebrates, who are currently numerous and diverse in the Antarctic Ocean ecosystem. However, not all species react in the same way. Some invertebrates show resilience

towards increased acidification, allowing for potential shifts toward species with a higher acidification tolerance (Watson et al., 2012).

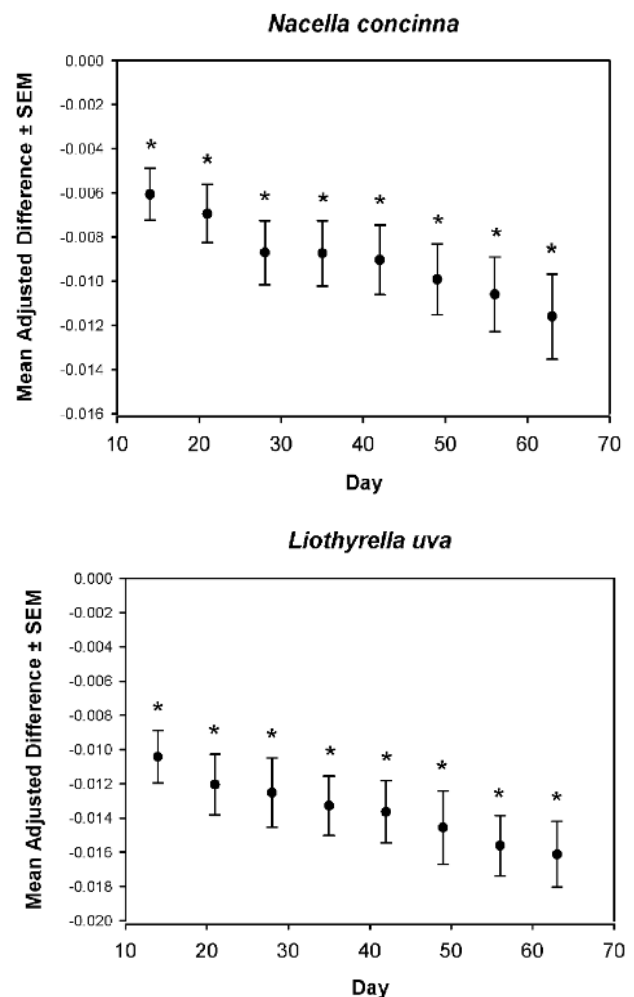


Figure 5: Mean adjusted differences in weight between shell halves subjected to seawater with pH 8.4 (control) and pH 7.4 (increased acidification) over time. Mean adjusted difference is calculated as the differences between control-acid weight difference on day 0 subtracted from control-acid weight difference on day x. Data shown for *Nacella concinna* (top) and *Liothyrella uva* (bottom) (adapted from McClintock et al., 2009)

In addition to shell strength, ocean acidification can also directly influence behaviour. An experiment with marine gastropod conch snails showed that increased acidification caused a lowered predatory-escape response (Watson et al., 2013). While motor functioning remained intact, behaviour was altered in such a way that steps to avoid predation were ignored (Figure 7).



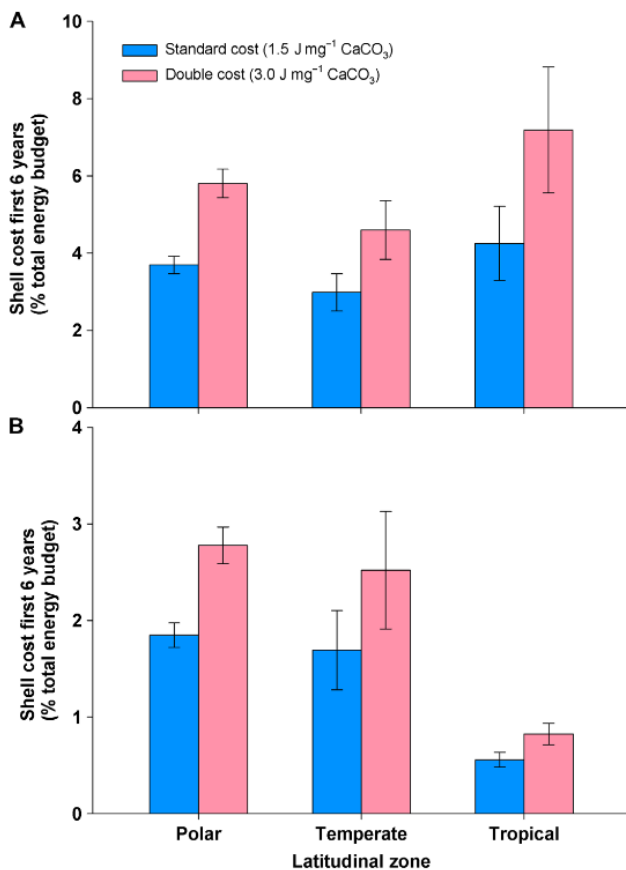


Figure 6: Shell production costs for A) gastropods and B) bivalves for normal costs (blue) and a hypothetical doubling of costs (pink). Polar and temperate regions share significantly higher costs than tropical species. (Watson et al., 2017)

For Antarctic invertebrates, who are already ill-prepared for predatory threats, this may increase their sensitivity to predation at seawater with lowered pH.

The difficulty in extracting CaCO<sub>3</sub> from cold waters may have attributed to the lack of durophagous predators in the Southern Ocean. These predators require CaCO<sub>3</sub> from ocean water to form their heavily calcified teeth (Aronson et al., 2007). While increased acidification poses threats to calcifying invertebrates, it might also mitigate some of the pressure that the predators can exert on them.

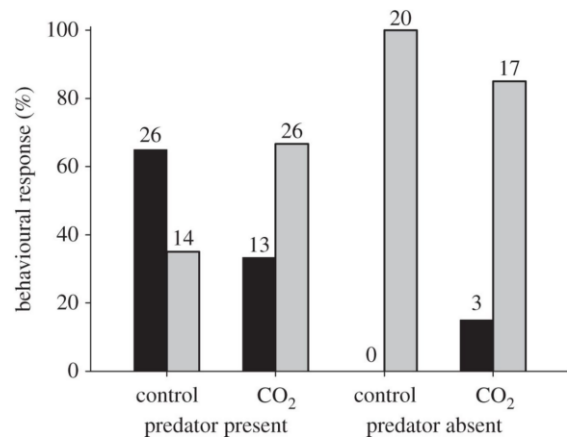


Figure 7: Behavioural response in marine conch snails under normal (control) and increased acidity (CO<sub>2</sub>). Numbers above the bars indicate replicates. Black bars depict jumping snails and grey non-jumping snails. (Watson et al., 2013)

### Current invasive threats

While the cold temperatures provide a barrier for invasion, there are certain hot-spots available in the Antarctic Ocean for invasive species to take refuge. One of these is the volcanic isle of Deception Island which can act as a safe-haven for invasive species and might allow them to slowly adapt to the colder conditions, providing pathways to radiate and populate the Southern Ocean (Aronson et al., 2015; Berrocoso et al., 2018). The ACC is also prone to form eddy formations, transporting species into the Southern Ocean. In a warming world, the threat of invasions into the Southern Ocean increases. Additionally, anthropogenic transport into the Antarctic has increased rapidly over the previous years. Since transport opportunities into the Antarctic have not been exhausted, an increase in transport is predicted in following years (Bender et al., 2016). Vessel transport into the Antarctic has been characterised as the main influx of invasive species in the Polar regions (Bender et al., 2016), mainly along the western side of the Antarctic Peninsula. While passive drift, flotsam and plastic substrates have been subjects of invasive facilitation, their main transport routes are through ocean

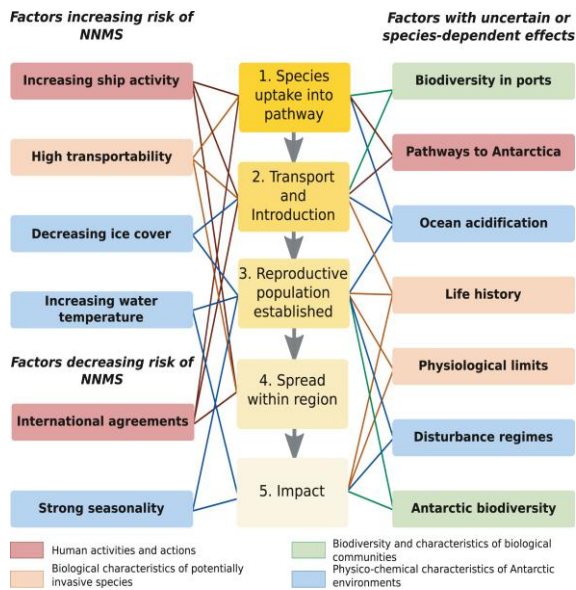


Figure 8: The 5 stages of the invasion process and the factors which influence the risk of non-native marine species (NNMS) (McCarthy et al., 2019)

currents, rarely ending up at the shore, and are distributed across a wide area (Lewis et al., 2005). Vessel transport provides many refuge locations for invasive species, ranging from sea chests to ballast water to hull fouling (Lee & Chown, 2007; Bender et al., 2016). Vessels also regularly visit many areas close to the coast in rapid succession and allow ample opportunity for invasive species to disembark in shallow waters (Lewis et al., 2005). Some vessels have even been reported to transport species from the Arctic into the Southern Ocean. The increased transportability of

invasive species combined with ocean warming is likely to result in stable invasive populations, which threaten the endemic wildlife (Chan et al., 2019) (Figure 8). After settling, invasive species can affect the native ecosystem in three ways:

- 1 They prey directly on the endemic species
- 2 They fulfil the same niche but outcompete the endemic species
- 3 They alter the environment to exclude the endemic species

Endemic Antarctic wildlife consists mainly of invertebrates. Their main predators, durophagous species like skates, sharks, and crabs have been excluded from the Antarctic Ocean because of their inability to regulate magnesium ions at cold temperatures. With present day ocean warming, the durophagous predators may have an opportunity to migrate southward and prey upon the near limitless food supply (Aronson et al., 2015; Inner, 2016). The durophagous brachyuran crab species *Halicarcinus planatus* has already been observed in the shallows at Deception island, a volcanic hotspot which can harbour invasive species (Berrocoso et al., 2018). Investigations into haemolyphic magnesium

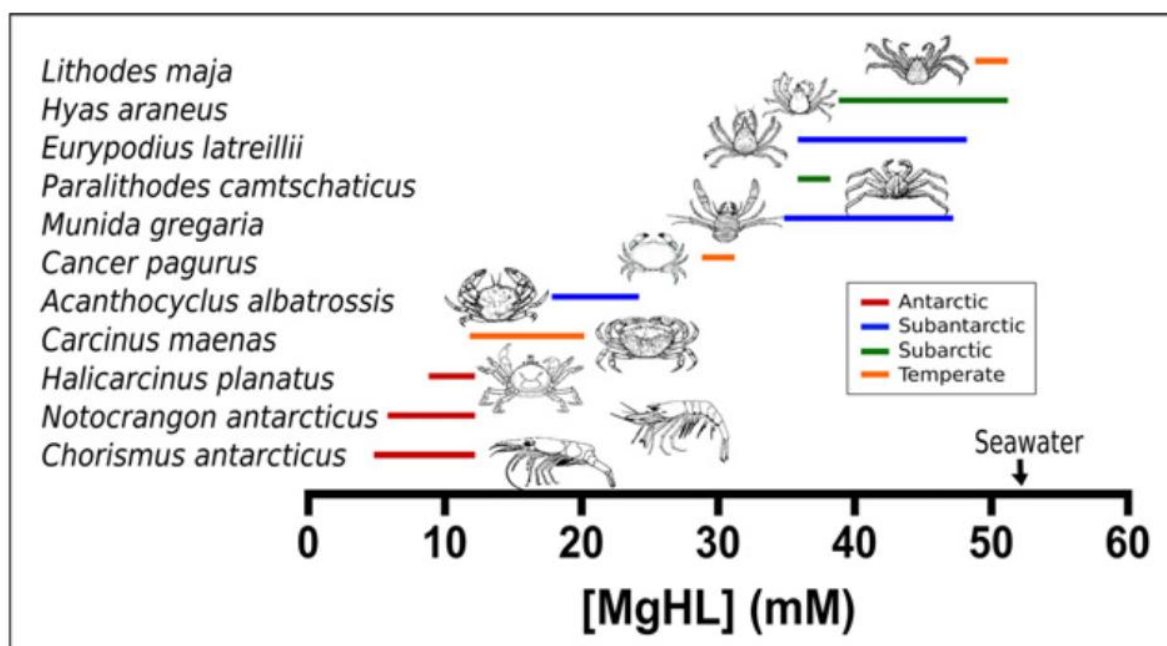


Figure 9: Haemolymph magnesium concentrations in different crustacean species (Aronson et al., 2015)

content of this species has shown that it is capable of down-regulating magnesium to a similar extent as certain Antarctic Caridean shrimp species (Figure 9) (Aronson et al., 2015). This provides a way of predicting possible invasive species, based on the variability of their ability to down-regulate haemolyphic magnesium ions.

Several Antarctic marine predatory invasion events have been recorded in recent years (Innes, 2016), with many debates about the invasion and southward expansion of the king crab (*Lithodes maja*) (Innes, 2016; Cowart et al., 2018). Based on their high haemolymph magnesium content (Figure 9), it is surprising that this species is able to survive in the Southern Ocean. However, this species has adapted to the cold way of life by slowing their growth and extending their breeding periods (Aronson et al., 2015). Lecithotrophy allows the larvae to survive without additional nutrients, feeding only on the yolk available to them. These adaptations allow this species to colonise the southern waters, displaying key pathways in which invasive species could invade the Antarctic marine communities (Aronson et al., 2015; Inner, 2016). While some believe the presence of *L. maja* is an indication that the ACC and PF barriers are faltering (Cowart et al., 2018), others claim that the crab species has been surviving and adapting in this area rather than being anthropogenically introduced (Griffiths et al., 2013). This is further complicated by ice-scour events, scraping away potential fossil records (Hellberg et al., 2019; Peck et al., 1999; Barnes, 2017). Regardless of introductory pathway, the southern location of the king crab poses concern for Antarctic benthic life. In light of future warming, these crabs might be able to migrate southwards and begin foraging on the endemic benthic population. These crabs have been shown to regulate ecosystems by administering top-down

control (Hellber et al., 2019; Innes, 2016). This might force the unique archaic benthic ecosystem to shift to a more temperate system, increasing homogenization (Aronson et al., 2007).

The brachyuran North Atlantic spider crab (*Hyas araneus*) has also been observed crossing the ACC barrier. This species has now been classified as an invasive species in the region (Table 1). While originally an Arctic species, anthropogenic influences has transported it into the Southern Ocean, allowing it to invade the Antarctic marine ecosystem (Tavares, 2004). Arctic marine species are already adapted to cold conditions, increasing their chances of surviving in the Southern Ocean. However, ocean acidification might counteract this threat. Increased acidity in ocean waters may increase the sensitivity of *H. araneus* to thermal shifts (Barnhart, 2001). Walther et al. (2009) showed that increased levels of CO<sub>2</sub> caused narrowing of the optimal temperature ranges of *H. araneus*. The result of this increased sensitivity combined with the warming of the oceans might counteract each other, making future predictions about the range of this species difficult. Three more Decapod invasion events have been recorded, namely the Brachyurans *Rochinia gracilipes*, *Pinnotheres* sp. and the Anomura *Emerita* sp. (Table 1) (Thatje & Fuentes, 2003; McCarthy et al., 2019, Griffiths et al., 2013). *Rochinia gracilipes* has only been observed once at high latitudes and has not been seen since. The *Pinnotheres* sp. and *Emerita* sp. observations have been only based on larval presence, signifying that the adult forms have lowered chances of transportability and survival. The current threat of durophagous predators invading the Antarctic Ocean is likely to increase due to future warming events and increase shipping activity, posing

Table 1: Non-native marine Antarctic species and their mechanisms of dispersal(Adapted from McCarthy et al., 2019). Threat level is based on literature research and accounts for current and future risk assessment. \* A score of 0 indicates unknown effects of invasion.

Species	Dispersal mechanism	Currently Invasive	Threat level index
<i>Halimacarcinus planatus</i>	Unknown	Yes	5
<i>Lithodes maja</i>	Unknown	Yes	5
<i>Hyas araneus</i>	Anthropogenic	Yes	5
<i>Rochinia gracilipes</i>	Unknown	Yes	4
<i>Pinnotheres</i> sp.	Natural	Yes	3
<i>Emeritia</i> sp.	Unknown	Yes	3
<i>Bugula neritina</i>	Anthropogenic	Yes	5
<i>Ciona intestinalis</i>	Anthropogenic	Yes	5
<i>Ectopleura crocea</i>	Anthropogenic	Yes	5
<i>Ulva intestinalis</i>	Natural and anthropogenic	Yes	0*
<i>Schizoporella unicornis</i>	N.A.	No	4
<i>Ascidella sparsa</i>	N.A.	No	4
<i>Mytilus galaprovincialis</i>	N.A.	No	4

significant dangers for the invertebrate wildlife of the Antarctic benthos.

Other species do not directly prey upon the endemic species but rather fulfil the same niche in a more energy-efficient way. Certain invertebrates, namely *Bugula neritina*, *Ciona intestinalis* and *Ectopleura crocea* (Gut et al., 2000; McCarthy et al., 2019), have crossed into the Antarctic Ocean. These are also considered invasive species in other habitats. Their main modes of transport is through ballast waters (McCarthy et al., 2019). Since these species have not paid the costs to adapt to cold environments, they have an increased growth rate and faster metabolic rate than the endemic Southern Ocean species. If temperatures allow the invasive invertebrates

to settle, their ability to take up nutrients at an increased rate allows them to outcompete the current species. This is further strengthened by reductions of Antarctic sea ice extent in summer, prolonging the short feeding period (Barnes & Clarke, 1995). This would increase food supply, ultimately favouring less-efficient species with increased growth rates (Cralke et al., 2013).

Similarly, opportunistic species with fast growth rates can take advantage of the potential increase in feeding period, combined with the effects of warming (Clark et al., 2013). r-strategists are primary settlers which are usually the first stage in succession processes. In the endemic communities, ice scour and limited food supply keeps the fast-

growing opportunists in check (Barnes et al., 2014). Invasive species however might be able to utilize the warming temperature and increased food supply to dominate benthic communities and reducing diversity. This would further increase the potential of homogenization and removal of unique ecosystems.

*Ulva intestinalis*, also known as gutweed, has also been observed as a settled invasive species in the Antarctic Ocean (Lewis et al., 2004; McCarthy et al., 2019). It has been found in ballast waters and is suspected of being transported into the Antarctic Ocean through anthropogenic means. The effects of this species on the endemic population however remains unexplored. In fact, the invasion of this species may be beneficial, as it may be used as nursery grounds or even as a refuge from predators, should they invade into the Antarctic Ocean. However, should conditions for this species become favourable, the increased nutrients and light availability during the feeding period may cause rapid growth, resulting in eutrophication effects which can be harmful for the native wildlife.

The previous explored species have all been observed in the Antarctic Ocean and are thus classified as invasive species. Several other species have not yet penetrated the Antarctic Ocean barriers, but have an increased chance of doing so when conditions become more favourable. Some of these species, specifically the Bryozoa *Schizoporella unicornis*, the Ascidian *Ascidiella aspersa* and the mussel *Mytilus galloprovincialis* have an increased threat potential due to their natural ranges being in the high latitudes, combined with the fact that they are considered invasive species elsewhere (McCarthy et al., 2019).

While invasion possibilities are prone to increase with increased transport,

physiological composition and thermal range will likely influence the chances for settlement of alien species. Certain Ascidians for example have been subject to repeated transport to temperate and sub-Antarctic locations. However, established settlements have only been observed in the temperate habitats, with none of the Ascidians being able to colonise the cold waters of the higher latitudes (Turon et al., 2016).

Since the invasive potential and effects on the endemic population vary per species, an assessment per species is necessary. The threat level index (Table 1) is a score varying from 1-5 (\*0 denotes unknown effects). 1 signifies little negative effects on the endemic wildlife, while a 5 indicates high-risk species which should be monitored for transport across the Antarctic Ocean. *H. planatus*, *L. maja* and *H. araneus* receive the highest risk assessment due to their durophagous behaviour, as well as their recent southern expansions. These species appear the most poised to create a reproductive establishment in the Southern Ocean. This combined with their high predatory capacity on the endemic population grants them the highest risk score. *R. gracilipes*, *Pinnotheres* sp. and *Emerita* sp. also have the ability to prey on the endemic wildlife and have been observed in the Antarctic Ocean in their larval state, however the adults do not appear to have the capacity to migrate southward and thus get a slightly lowered score. *B. neritina*, *C. intestinalis* and *E. crocea* have all been transported by anthropogenic means. They have also been observed as invasive species in other areas, making them a strong contender for invasion into the Antarctic community with negative consequences for endemic life. *S. unicornis*, *A. aspersa* and *M. galloprovincialis* have not yet been observed in the Southern Ocean but display tolerances to high latitudes, as well as the potential to become invasive threats. *Ulva*

*intestinalis* has been observed at several locations in the Southern Ocean, however, its impacts on the local communities has yet to be explored in detail.

### **Guidelines and Policies**

While several species have been able to traverse the barriers in the Southern Ocean, the impact of their invasion has remained relatively low. Harsh conditions inhibit activity rates and reduce grazing pressures, resulting in slow reproduction rates. This has led to the fact that, while several species have been denoted as invasive, there have not yet been records of established reproductive populations (Figure 8, step 3) (McCarthy et al., 2019). However, elevated sea-surface temperatures in combination with increased vessel transport into the Antarctic vastly increase the potential for alien species to colonise the Antarctic. The stenothermal endemic species, which are already threatened by the increased temperatures, will have little probability of surviving invasion events, whether predatory or not. Therefore, appropriate actions need to be taken in order to protect the pristine ecosystem of the Antarctic benthos. Regimes need to be implemented to hinder the main transport route of the invasive species, anthropogenic vessel transport. This can be done in two ways: limit the amount of ships that can dock at Antarctic shores throughout the year or invest in novel antifouling methods, reducing the chances of alien species attaching themselves to ships. Ballast water is also a point of investigation, being a source for invertebrate invasive species.

### **Further investigation**

Numerous invasion events have been documented including durophagous crab species and several invertebrates, however

the impact of their colonisation has been relatively unexplored. Effects of grazing and competition remains unpredictable, especially considering changes in sea-surface temperature and ocean acidification and should therefore be investigated.

Endemic stenothermal communities are extremely sensitive to environmental changes. Should global warming threaten these communities to extinction, opportunities for invasive species to adopt this habitat might arise, rather than leave it as a barren wasteland in worst case scenarios. Positive effects of invasion seem unlikely, but should the endemic community fail to acclimate to the rapid warming, invasive species might provide an inhibitory function to prevent algal-dominated systems. Ecosystem functioning shifts are likely to play important roles following invasion events but are currently under-examined.

### **Conclusion**

Anthropogenic warming has cast great concerns regarding the future state of the unique Antarctic marine ecosystem. Since this community has adapted in isolation of predators, the effects of invasive species are potentially devastating. While the Antarctic peninsula has been thoroughly studied for alien species, the same cannot be said for the marine system. Invasive species are a significant cause for concern due to their ability to diminish the local fauna, be it by directly preying upon them or causing community shifts by competitive exclusion. Effects of warming and acidification further enhance the difficulties that the Antarctic marine life is facing. In order to preserve this habitat and reduce global homogenization, steps must be taken to limit the potential for invasive events, primarily by decreasing vessel transport into the Antarctic. While invasive

species seem detrimental to the Antarctic benthos, many questions remain unanswered regarding their effects on the local wildlife in a world dominated by global change.

## References

- Aronson, R. B., Frederich, M., Price, R., & Thatje, S. (2015). Prospects for the return of shell-crushing crabs to Antarctica. *Journal of Biogeography*, 42(1), 1-7.
- Aronson, R. B., Thatje, S., Clarke, A., Peck, L. S., Blake, D. B., Wilga, C. D., & Seibel, B. A. (2007). Climate change and invasibility of the Antarctic benthos. *The Annual Review of Ecology, Evolution, and Systematics*, 38, 129–154.
- Ashton, G. V., Morley, S. A., Barnes, D. K. A., Clark, M. S., & Peck, L. S. (2017). Warming by 1°C drives species and assemblage level responses in Antarctica's marine shallows. *Current Biology*, 27(17), 2698–2705.e3.
- Barnes, D. K. A. (2017). Iceberg killing fields limit huge potential for benthic blue carbon in Antarctic shallows. *Global Change Biology*, 23, 2649–2659.
- Barnes, D. K. A., & Clarke, A. (1995). Seasonality of feeding activity in Antarctic suspension feeders. *Polar Biology*, 15, 335–340.
- Barnes, D. K. A., & Souster, T. A. (2011). Reduced survival of Antarctic benthos linked to climate-induced iceberg scouring. *Nature Climate Change*, 1(7), 365–368.
- Barnes, D. K., Fenton, M., & Cordingley, A. (2014). Climate-linked iceberg activity massively reduces spatial competition in Antarctic shallow waters. *Current Biology*, 24(12), R553-R554.
- Barnhart, H. (2001). Distribution patterns of decapod crustaceans in polar areas: A result of magnesium regulation? *Polar Biology*, 24(10), 719–723.
- Bender, N. A., Crosbie, K., & Lynch, H. J. (2016). Patterns of tourism in the Antarctic Peninsula region: a 20-year analysis. *Antarctic Science*, 28(3), 194-203.
- Berrocoso, M., Prates, G., Fernández-Ros, A., Peci, L. M., de Gil, A., Rosado, B., ... & Jigena, B. (2018). Caldera unrest detected with seawater temperature anomalies at Deception Island, Antarctic Peninsula. *Bulletin of Volcanology*, 80(4), 41.
- Chan, F. T., Stanislawczyk, K., Sneekes, A. C., Dvoretzky, A., Gollasch, S., Minchin, D., ... & Bailey, S. A. (2019). Climate change opens new frontiers for marine species in the Arctic: Current trends and future invasion risks. *Global change biology*, 25(1), 25-38.
- Clark, G. F., Stark, J. S., Johnston, E. L., Runcie, J. W., Goldsworthy, P. M., Raymond, B., & Riddle, M. J. (2013). Light-driven tipping points in polar ecosystems. *Global Change Biology*, 19(12), 3749-3761.
- Clarke, A., Murphy, E. J., Meredith, M. P., King, J. C., Peck, L. S., Barnes, D. K. A., & Smith, R. C. (2007). Climate change and the marine ecosystem of the western Antarctic Peninsula. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 362(1477), 149–166.
- Cook, A. J., & Vaughan, D. G. (2010). Overview of areal changes of the ice shelves of the Antarctic Peninsula over the past 50 years. *The Cryosphere*, 4(1), 77–98.
- Cowart, D. A., Murphy, K. R., & Cheng, C. H. C. (2018). Metagenomic sequencing of environmental DNA reveals marine faunal assemblages from the West Antarctic Peninsula. *Marine genomics*, 37, 148-160.
- Griffiths, H. J., Meijers, A. J. S., & Bracegirdle, T. J. (2017). More losers than winners in a century of future Southern Ocean seafloor warming. *Nature Climate Change*, 7(October), 749–756.
- Griffiths, H. J., Whittle, R. J., Roberts, S. J., Belchier, M., & Linse, K. (2013). Antarctic crabs: Invasion or endurance? *PLoS ONE*, 8(7), e66981.

Gutt, J., Sirenko, B., & Arntz, W. (2000). Biodiversity of the Weddell Sea: macrozoobenthic species (demersal fish included) sampled during the expedition ANT XIII/3 (EASIZ I) with RV "Polarstern". *Berichte zur Polarforschung (Reports on Polar Research)*, 372.

Hellberg, M. E., Aronson, R. B., Smith, K. E., Duhon, M. I., Ayong, S. T., Lovrich, G. A., ... & McClintock, J. B. (2019). Population expansion of an Antarctic king crab?. *Frontiers of Biogeography*.

Innes, R. (2016). Antarctic Lithodids (King Crabs): Climate Change and Threats to Antarctic Marine Ecosystems.

Lee, J. E., & Chown, S. L. (2007). *Mytilus* on the move: transport of an invasive bivalve to the Antarctic. *Marine ecology progress series*, 339, 307-310.

Lewis, P. N., Riddle, M. J., & Smith, S. D. A. (2005). Assisted passage or passive drift: A comparison of alternative transport mechanisms for non-indigenous coastal species into the Southern Ocean. *Antarctic Science*, 17(2), 183–191.

McClintock, J. B., Angus, R. A., McDonald, M. R., Amsler, C. D., Catledge, S. A., & Vohra, Y. K. (2009). Rapid dissolution of shells of weakly calcified Antarctic benthic macroorganisms indicates high vulnerability to ocean acidification. *Antarctic Science*, 21(5), 449-456.

Meredith, M. P., & King, J. C. (2005). Rapid climate change in the ocean west of the Antarctic Peninsula during the second half of the 20th century. *Geophysical Research Letters*, 32(19), L19604.

Morley, S. A., Lurman, G. J., Skepper, J. N., Pörtner, H. O., & Peck, L. S. (2009). Thermal plasticity of mitochondria: A latitudinal comparison between Southern Ocean molluscs. *Comparative Biochemistry and Physiology - A Molecular and Integrative Physiology*, 152(3), 423–430.

Morley, S. A., Tan, K. S., Day, R. W., Martin, S. M., Pörtner, H. O., & Peck, L. S. (2009). Thermal dependency of burrowing in

three species within the bivalve genus *Laternula*: A latitudinal comparison. *Marine Biology*, 156(10), 1977–1984.

Peck, L. S. (2016). A cold limit to adaptation in the sea. *Trends in Ecology and Evolution*, 31(1), 13–26.

Peck, L. S. (2018). Antarctic marine biodiversity: Adaptations, environments and responses to change. *Oceanography and Marine Biology: an Annual Review*, 56, 105–236.

Peck, L. S., Brockington, S., Vanhove, S., & Beghyn, M. (1999). Community recovery following catastrophic iceberg impacts in a soft-sediment shallow-water site at Signy Island, Antarctica. *Marine Ecology Progress Series*, 186, 1–8.

Peck, L. S., Morley, S. A., Richard, J., & Clark, M. S. (2014). Acclimation and thermal tolerance in Antarctic marine ectotherms. *Journal of Experimental Biology*, 217(1), 16–22. <https://doi.org/10.1242/jeb.089946>

Power, C. (2018). Ocean warning! A review of climate change effects on Antarctic marine ecosystems.

Tavares, M., & De Melo, G. A. (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., & Fuentes, V. (2003). First record of anomuran and brachyuran larvae (Crustacea: Decapoda) from Antarctic waters. *Polar Biology*, 26(4), 279-282.

Turon, X., Cañete, J. I., Sellanes, J., Rocha, R., & López-Legentil, S. (2016). Too cold for invasions? Contrasting patterns of native and introduced ascidians in subantarctic and temperate Chile. *Management of Biological Invasions*, 7(1), 77–86.

Walther, K., Sartoris, F. J., Bock, C., & Pörtner, H. O. (2009). Impact of anthropogenic ocean acidification on thermal



tolerance of the spider crab *Hyas araneus*. *Biogeosciences*, 6(10), 2207-2215.

Watson, S. A., Lefevre, S., McCormick, M. I., Domenici, P., Nilsson, G. E., & Munday, P. L. (2013). Marine mollusc predator-escape behaviour altered by near-future carbon dioxide levels. *Proceedings of the Royal Society B: Biological Sciences*, 281(1774), 20132377–20132377.

Watson, S. A., Morley, S. A., & Peck, L. S. (2017). Latitudinal trends in shell production cost from the tropics to the poles. *Science Advances*, 3(9), e1701362–

Watson, S. A., Peck, L. S., Tyler, P. A., Southgate, P. C., Tan, K. S., Day, R. W., & Morley, S. A. (2012). Marine invertebrate skeleton size varies with latitude, temperature and carbonate saturation: Implications for global change and ocean acidification. *Global Change Biology*, 18(10), 3026–3038.

Wittmann, A. C., Held, C., Pörtner, H. O., & Sartoris, F. J. (2010). Ion regulatory capacity and the biogeography of Crustacea at high southern latitudes. *Polar Biology*, 33(7), 919-928.