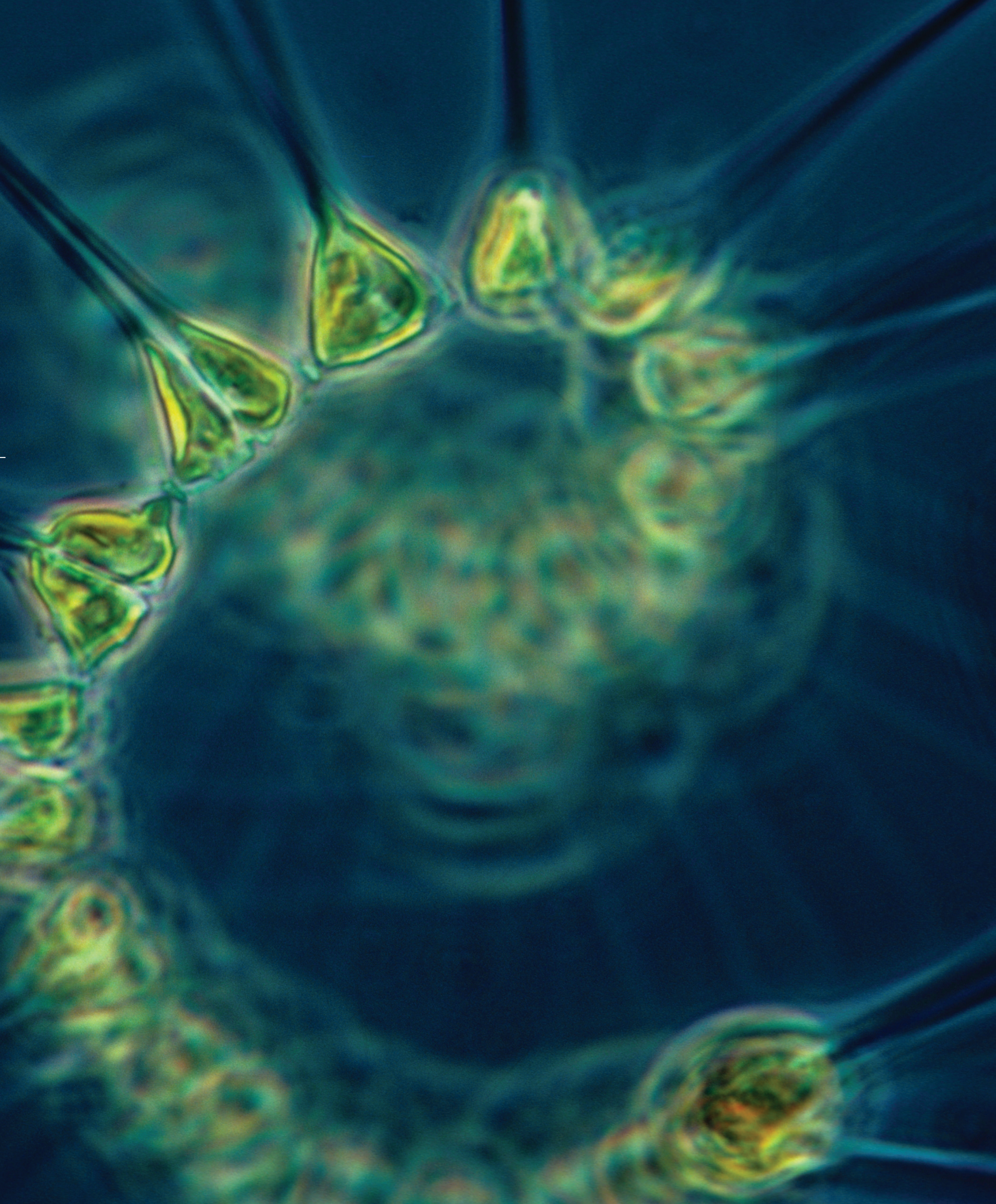
# ACE CRC Report Card

**POTENTIAL TIPPING POINTS FOR LIFE IN THE SOUTHERN OCEAN**



ANTARCTIC CLIMATE & ECOSYSTEMS
COOPERATIVE RESEARCH CENTRE

Australian Government
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Report Card: Potential Tipping Points for life in the Southern Ocean

**Scientific Contributors**
Philip Boyd
So Kawaguchi
Robert Strzepek
Klaus Meiners
Gustaaf Hallegraeff
Andrew McMinn
Kerrie Swadling

**Other Contributors**
David Reilly

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Antarctic Climate & Ecosystems
Cooperative Research Centre
Private Bag 80, University of Tasmania
Hobart Tasmania 7001

**Tel:** +61 3 6226 7888
**Email:** enquiries@acecrc.org.au
**www.acecrc.org.au**

**Cover image:** A phytoplankton cell.

The Antarctic Climate & Ecosystems CRC is Australia's primary vehicle for understanding the role of the Antarctic region in the global climate system, and the implications for marine ecosystems. Our purpose is to provide governments, industry and the public with accurate, timely and actionable information on climate change and its likely impacts.

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# INTRODUCTION

There is now clear scientific evidence that the increasing magnitude and rate of anthropogenic carbon dioxide ($CO_2$) emissions are causing rapid and unprecedented changes to the global ocean. These will have potentially serious impacts during the 21st century on the sustainability and management of many marine and coastal ecosystems. Research has shown that the Southern Ocean, in particular, is encountering significant changes linked to climate change. The changes in pH, temperature, circulation and sea ice – along with potential for increased fishing pressure – are all likely to have far-reaching consequences for all species that currently inhabit the Southern Ocean.

One of the fundamental questions for marine scientists studying the Southern Ocean is how climate change will alter the growth of key prey species including phytoplankton, zooplankton and krill. Phytoplankton are the base of the marine food web, and even seemingly small changes in sea-ice, ocean circulation, chemistry and temperature will affect which species live, thrive and die in the ocean. The biological outcomes from these changes will be determined by the environment, timing, rate and magnitude of change in each stressor, the order in which the changes occur, and the potential for consequences to be compounded when multiple stressors change concurrently. Hence, understanding the impacts of climate change on Southern Ocean life requires us to consider which key species will be more sensitive to change, if change will have benefical or detrimental effects on marine life, and how change will vary from region to region. These new scientific insights will have important implications for management of fish stocks and high conservation value species throughout the region.

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Baleen whale.

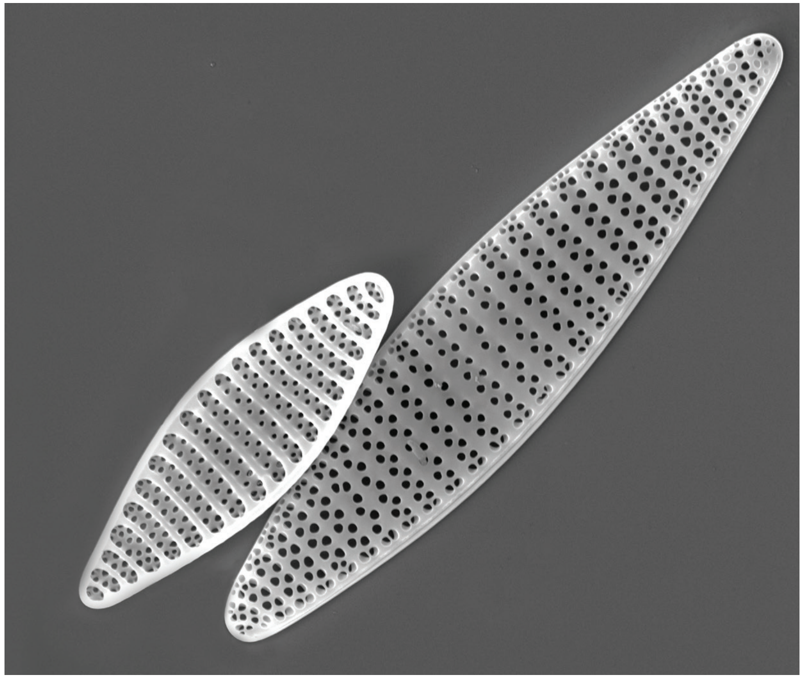
## Aims:

- To provide an update on the latest developments in understanding the potential biological tipping points for the biota that comprise Southern Ocean ecosystems, highlighting the ACE CRC's recent activities and niche in this expanding research area.
- To consider the potential broader ecological impacts of these changes under future climate change scenarios; and
- To identify key challenges and areas for further research.

# ANTARCTICA'S ISOLATION

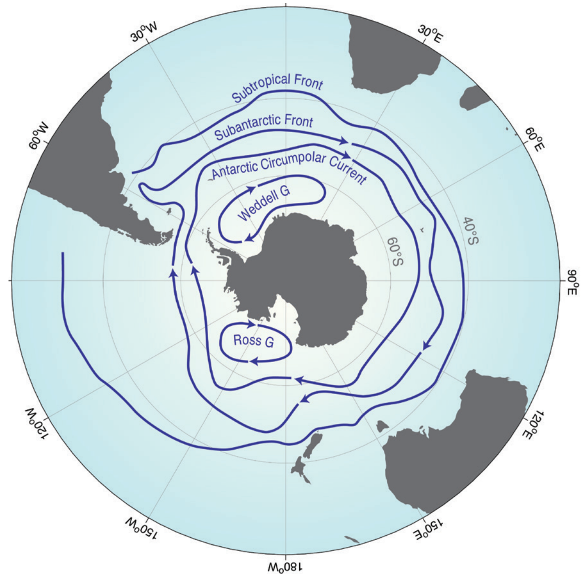
Despite the harsh climate and geographical isolation, Antarctica and the Southern Ocean are home to an abundance of species that thrive in cold conditions. The combination of environmental extremes and geographical isolation over millions of years has produced an ecosystem unlike any other, with a fascinating array of uniquely adapted species. Sea ice algae, instead of blooming on the warm and sunlit surface of the ocean like most phytoplankton, spend the long, dim winter colonising the underside of the sea ice. The sea ice also provides a refuge for billions of Antarctic krill, which boost their growth by grazing on the algae during winter before the spring ice melt releases them into the open ocean in large swarms. The abundance of krill in the Southern Ocean provides enough food to sustain a great number and variety of specially adapted marine mammals, birds and fish, along with migratory species such as the baleen whales that return from the tropics every year.

The key reason for the region's isolation from the rest of the world ocean is the vast Antarctic Circumpolar Current (ACC), which flows clockwise around the landmass driven by westerly winds (Figure 1). This suite of 'fronts' acts as an insulating barrier that traps the cold waters at high latitudes and keeps the continent frozen. The sudden shift from warm to cold also serves as a barrier to the movement of polar marine life, many of which have become uniquely adapted (i.e. 'hard-wired') to the challenges of living in an extreme environment. Understanding how this 'hard-wiring' works is therefore essential in assessing how Antarctic life will respond in the future where the climate is changing at an unprecedented rate, since the cost of adapting to life in a harsh and isolated environment is likely a vulnerability to such relatively sudden change.



*Fragilariopsis kerguelensis* – one of the many forms of microscopic plankton native to the Southern Ocean.

**FIGURE 1:** Antarctica is surrounded by a series of circumpolar features such as the Antarctic Circumpolar Current and the Subtropical Front, which can act as barriers and maintain the geographical isolation of free-drifting life in the surface waters of the Southern Ocean (modified from Rintoul 2000).



# OCEAN CIRCULATION

A dive to the depths of the Southern Ocean reveals the isolation encountered by upper ocean life forms due to the barriers imposed by ocean fronts is not evident in the deep ocean (Figure 2). Here, at depth, silent massive flows of ocean currents move waters northwards. Hence, the Southern Ocean is isolated at shallow depths, but intimately connected with, and highly influential on, global processes at intermediate depths and beyond. This connectivity is best known as the overturning thermohaline circulation.

The flow of deep water from the Southern Ocean also plays an important role in supplying and sharing part of the vast reservoir of plant nutrients such as nitrate and phosphate to much of the global ocean. This current lifts cold, nutrient-rich waters from the deep sea to the surface, a process known as upwelling. The nutrients stimulate blooms of phytoplankton and sea ice algae, which form the base of the Antarctic foodwebs.

This vital service to the global ocean is sometimes termed the nutrient conveyor. The nutrients can be supplied because not all of them are being consumed in polar or subpolar waters by the resident plankton (Figure 1).

Mathematical models have shown that this conveyor can drive up to a third of the biological growth, also known as productivity, in subtropical and tropical low latitude oceanic regions.

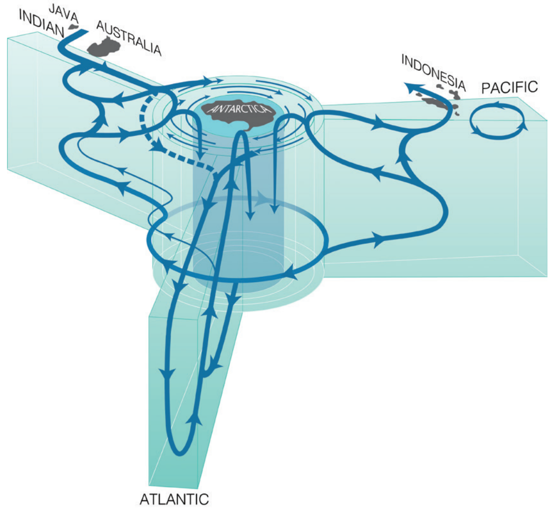
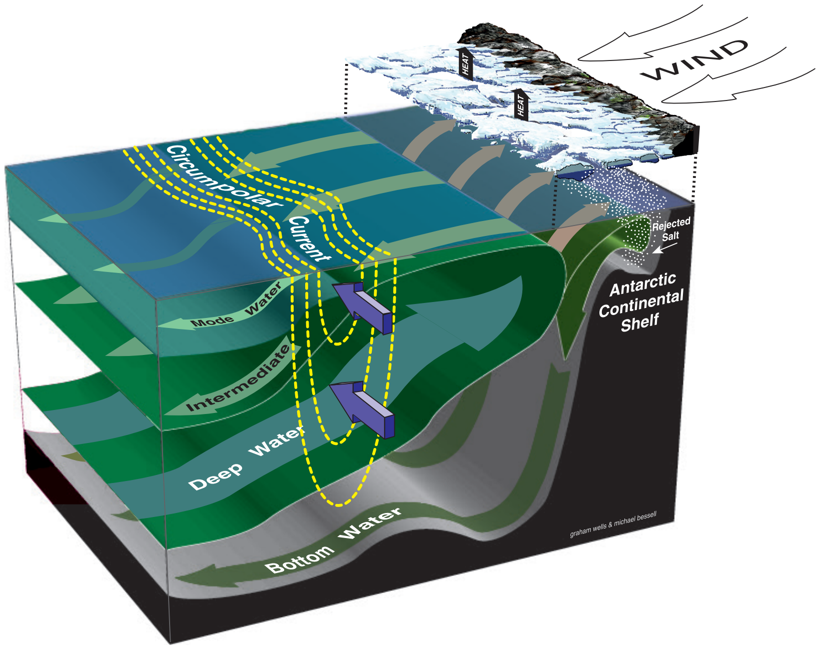



**FIGURE 2:**
The water masses that make up the Southern Ocean are highly dynamic and are transported into each of the Atlantic, Indian and Pacific basins at intermediate and great depths. In turn, other waters from these basins flow towards Antarctica (adapted from Talley 2013).

**FIGURE 3:**
The overturning cell of the Antarctic Circumpolar Current (ACC) prevents significant north-south transport of surface waters across its boundary (Rintoul 2000).



# UNIQUE MARINE LIFE - ADAPTED TO SOUTHERN OCEAN EXTREMES

Is the isolation of the surface waters of the Southern Ocean by the ACC (Figure 3) reflected by characteristics of its marine biota? There is a growing body of evidence that supports the idea that marine life in the surface ocean, such as marine phytoplankton at the base of the foodweb, are uniquely adapted to the many extremes that life in the Southern Ocean entails. This evidence has been gleaned mainly by looking at the 'hard-wiring' of polar life – by looking inside the cell at their genes which preserve a record of the adaptations to environmental extremes that include cold waters, low light levels and vanishingly low levels of the essential trace element iron (without which the cells become anaemic and perform poorly).

A recent international study by Mock et al. (2017) investigated the gene library of a small (5 micron) sea-ice and open water diatom (a type of phytoplankton) – *Fragilariopsis cylindrus*. They reported that this diatom had a much larger than normal gene pool than phytoplankton species from the low latitude ocean. This vast gene pool allows it to thrive under the highly variable environmental conditions of the Southern Ocean, such as coping with changes from total darkness to light (winter to spring), polar temperatures, and changes in the supply of iron (Mock et al., 2017). There is also anecdotal evidence from collaborators that krill may have a massive gene pool that is thought to enable them to live in a wide range of environments such as under sea-ice, the surface ocean and the deep sea.

Research within the ACE CRC by Strzepek et al. (2019) delved inside the site of photosynthesis within polar phytoplankton that had been isolated in the far south and brought to the ACE CRC labs in Hobart. ACE CRC researchers compared how much of the essential trace element iron was needed to drive the engine room for photosynthesis – the photosystems in the chloroplast. It turns out that polar species featured in Figure 4 have all developed a similar strategy whereby they need much less iron for photosynthesis – even when iron is scarce, as it is much of the time in the Southern Ocean – than their counterparts in the temperate waters north of the Southern Ocean. This efficiency is all the more remarkable as it has likely been developed under low light conditions (which usually increase iron demand) and at low temperatures. Strzepek et al. (2019) concluded these remarkable adaptations (i.e. hard-wiring) have led to a more productive Southern Ocean than should be possible under such harsh conditions for marine life. How will these advantages play out now that the region is encountering an unprecedented rate of change in many ocean properties (Figure 5)?

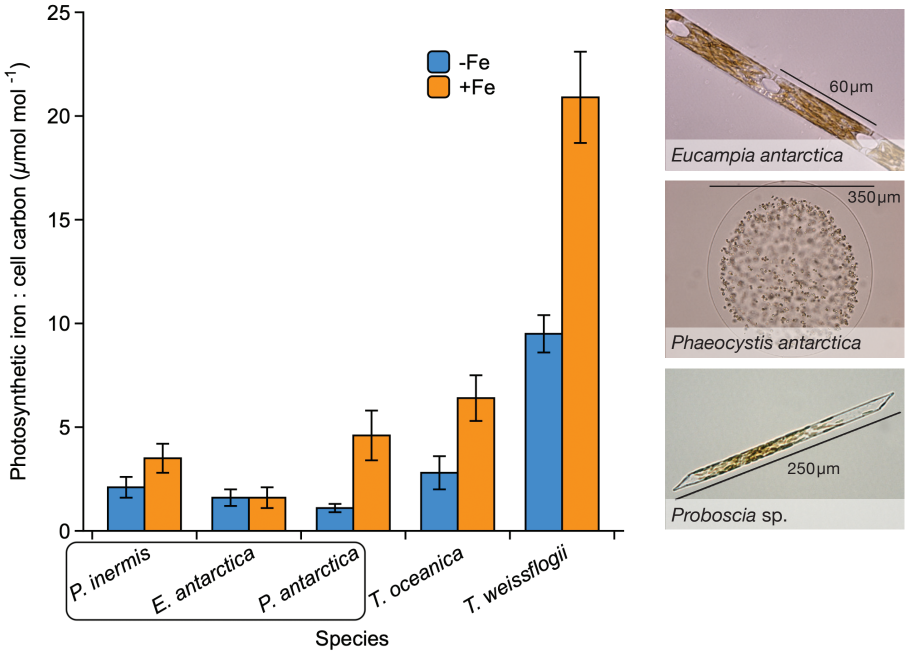



**FIGURE 4:**
The amount of iron needed for photosynthesis is much lower in Southern Ocean phytoplankton (within the box) than for phytoplankton from warmer temperate waters (adapted from Strzepek et al., 2019).

# THE SOUTHERN OCEAN AND ANTARCTICA ARE CHANGING

- The Southern Ocean and Antarctica are undergoing complex multi-faceted changes during the Anthropocene.
- Changes in the ozone hole overlying this region are also playing a role by influencing the westerly wind belt, which drives key processes including sea ice formation, ocean stratification and circulation.
- The Southern Ocean is taking up a large proportion of anthropogenic emissions, leading to increased ocean acidification.
- The increased $CO_2$ in the atmosphere results in the warming of the atmosphere and the ocean.
- A warming ocean and changes in its salt content (ice melt and changes in precipitation) are altering the density stratification of the upper ocean, and hence the degree of communication between the surface waters and the oceans interior.
- Increased stratification is changing the supply of nutrients to surface waters and of oxygen to the deep sea.
- Changing westerly winds (intensity and latitudinal banding) are influencing the depth of the surface mixed layer, and hence the mean light levels in the surface ocean where phytoplankton reside. They supply energy to foodwebs. Melting of sea ice can also influence the underwater light climate.
- Together, acidification, warming, and changes in irradiance, nutrients and trace elements such as iron will influence the stocks and productivity of Southern Ocean life.

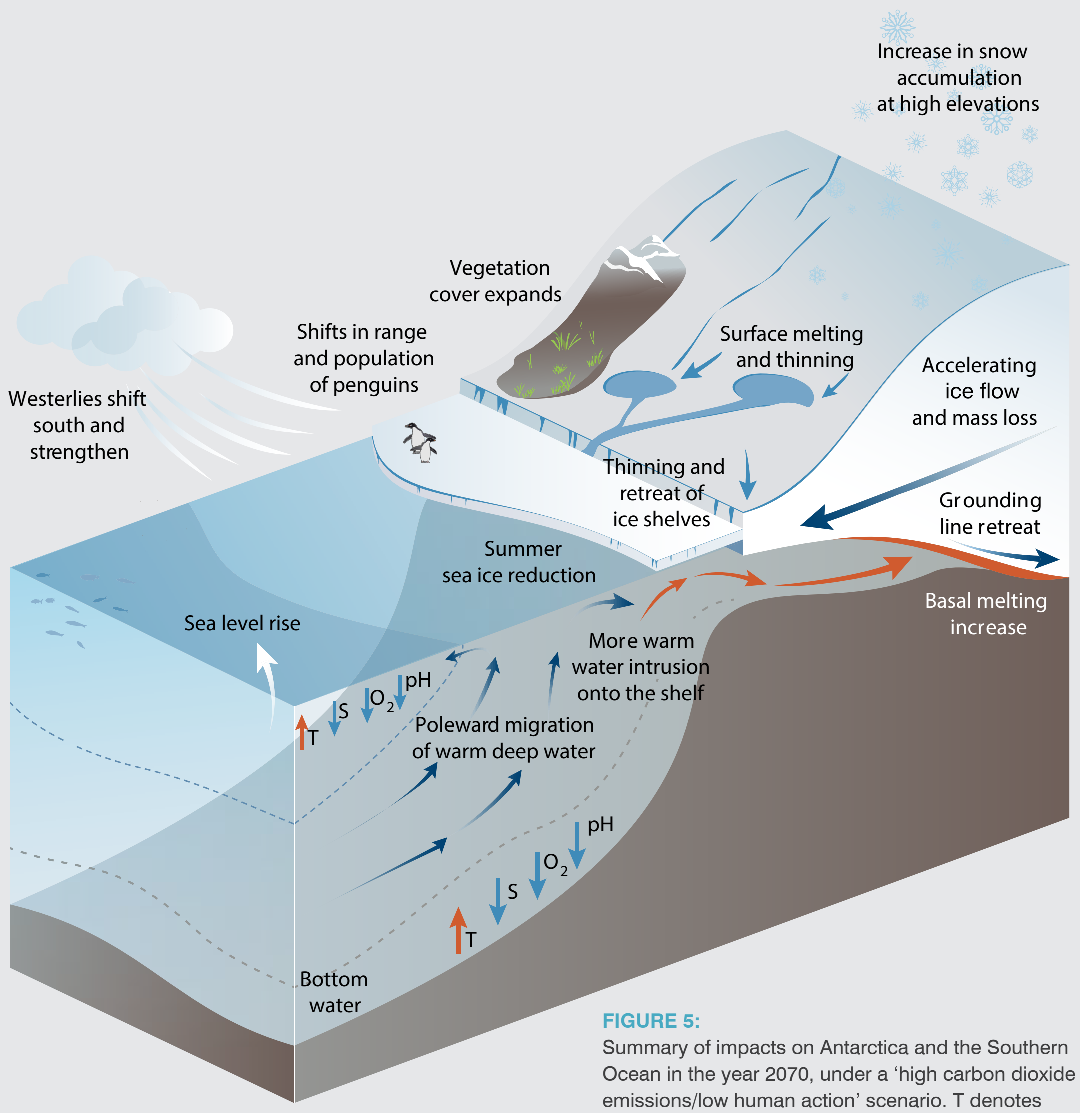



**FIGURE 5:**
Summary of impacts on Antarctica and the Southern Ocean in the year 2070, under a 'high carbon dioxide emissions/low human action' scenario. T denotes temperature; S, salinity; $O_2$, oxygen, pH is a measure of acidity (modified from Rintoul et al., 2018).

# UNDERSTANDING BIOLOGICAL TIPPING POINTS

How will this long-adapted group of polar and subpolar organisms respond to relatively rapid – years to decades – changes in open water and sea-ice conditions? Will we see dramatic shifts – often termed as tipping points (defined as the time at which a change or an effect cannot be stopped)?

The Southern Ocean and Antarctica can be divided into regions, each with distinct habitats for marine biota. As the temperature, salinity, pH and other factors continue to change, the subpolar, polar, marginal ice zone, and cryosphere will each be imprinted with differing impacts and degrees of change. Model projections for the year 2100 (Boyd et al., 2015) suggest the surface waters south of Australia will warm by approximately 3°C in the sub-Antarctic – whereas those in the polar Southern Ocean will warm by about 1.5°C, relative to the global mean ocean warming of 2.5°C.

There are additional differences between these regions including the type of marine life that thrives in each region (Boyd et al., 2015). Each of these groups of diverse marine life forms will in many cases be influenced by a different set of drivers (or stressors), increasing the number of permutations that may have to be considered in any assessment of how anthropogenic climate change will influence Southern Ocean biota. Many of these biological drivers will be altered by anthropogenic change concurrently.

Developing an effective research methodology for assessing these changes is a considerable challenge, given the extremely wide range of permutations and possibilities across multiple habitats, organisms, and drivers. Prioritising the ACE CRC's research focus has therefore required the construction of an inventory of the multiple drivers that influence organisms at each level of the food web from phytoplankton, to benthic sea floor grazers to water column grazers such as krill (Figure 6).

Following development of this suite of inventories, ACE CRC researchers have begun developing experimental methods aimed at understanding the environmental conditions that influence the growth of phytoplankton, and how they might change during the coming decades under a variety of projected ocean conditions, by measuring each organism's response to those projected changes. Researchers have completed the first laboratory experiments aimed at 'stress testing' selected dominant Southern Ocean species. These pilot experiments are designed to ascertain what the dominant environmental drivers were in each of the multiple driver inventories.

Where experiments to date have tended to focus on the effect of changes in individual properties such as pH or temperature, ACE CRC studies have begun considering a more complex matrix of multiple drivers, including light, nutrients, carbon dioxide, temperature and iron, to gain an understanding of how these drivers interact and of their combined effects on phytoplankton (Boyd et al., 2016).

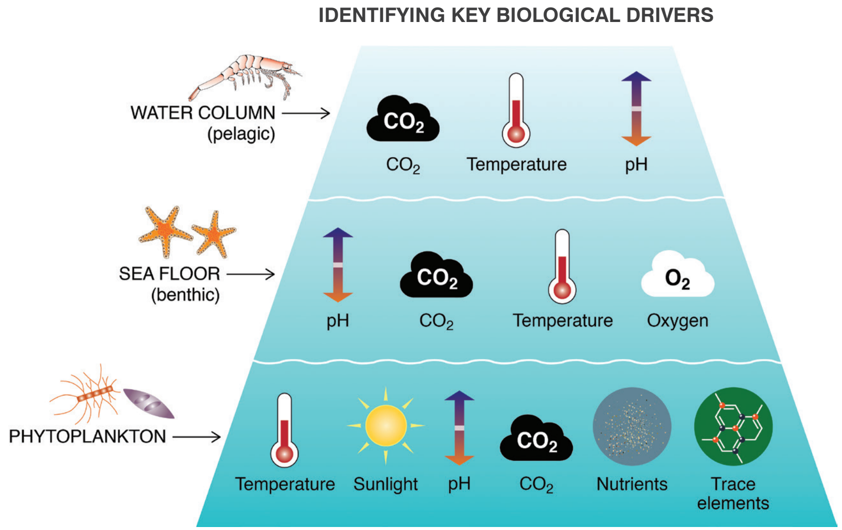


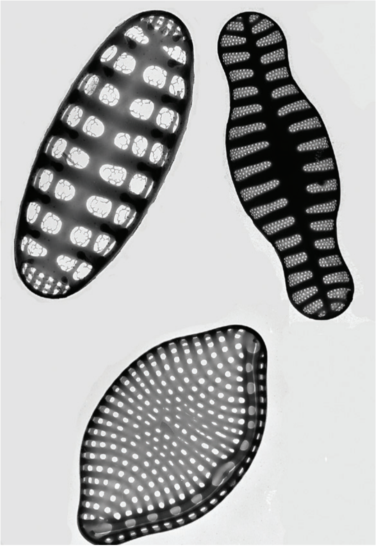

**FIGURE 6:** Schematic to illustrate how the environmental drivers that influence marine life differ between the trophic levels in a Southern Ocean foodweb. Primary producers such as the phytoplankton form the base of the foodweb (represented by the trapezoid). They photosynthesise and so they require sunlight and nutrients, but are also influenced by other drivers such as temperature. At higher trophic levels starfish (benthic – living on the sea floor) and krill (pelagic – living in the water column) are influenced by different drivers, including oxygen levels on the sea floor.

# EXPERIMENTAL OUTCOMES

The following two examples outline some key early findings from laboratory experiments aimed at 'stress testing' key Southern Ocean species under future projected climate scenarios. These experiments represent a subset of the many possibilities of drivers, marine life and habitats in the region (Figure 7). In both experiments, researchers set up simulated Southern Ocean conditions inside incubation facilities at the University of Tasmania's Institute for Marine and Antarctic Studies, and at the Australian Antarctic Division's krill aquarium. By recreating subpolar and polar environments, the researchers were able to successfully manipulate the 'control' environments to mimic potential future conditions and observe the outcomes. In other examples, the researchers conducted experiments designed to understand how organism isolated for centuries and longer by circumpolar barriers were adapted, looking at how long term exposure to particular conditions, such as temperature, affected their performance.

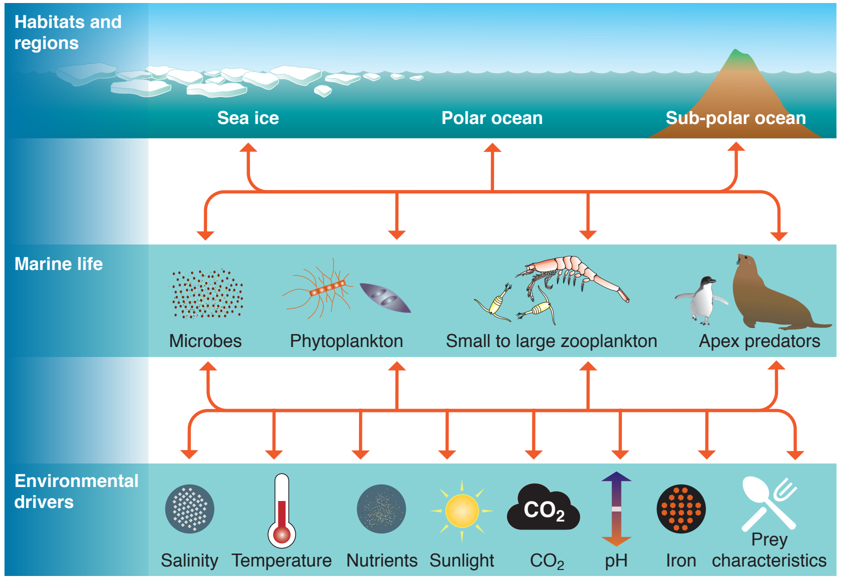
Australian Antarctic Division

Krill aquarium at the Australian Antarctic Division.



Planktonic diatoms.

**FIGURE 7:**
Understanding a complex system – this diagram reveals the many permutations that exist for Southern Ocean biota with respect to how they will respond to changing environmental conditions. There are distinctive regional differences in habitat – from the sub-Antarctic to polar waters and south to the marginal ice zone and cryosphere. Each region will encounter different changes to biologically influential environmental drivers. Each part of the foodweb (termed trophic level) will be influenced by different drivers. This structure helped to design the framework for the report card.



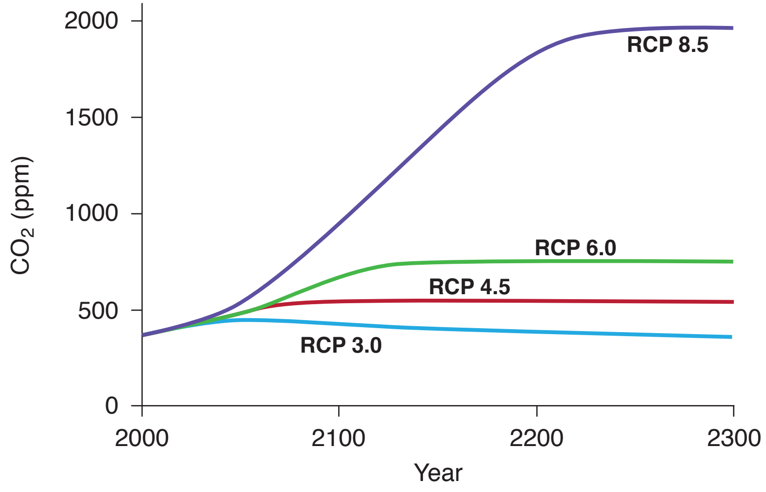
## KRILL

A key experiment by ACE CRC-affiliated researchers at the Australian Antarctic Division has examined the potential susceptibility of krill to ocean acidification (decrease in pH due to higher $CO_2$). With a complex life cycle comprising more than 10 stages from egg to adult, the study examined how early krill life stages are influenced by increased acidification (Kawaguchi et al., 2013).

To identify projected future ocean pH levels, they used a three-dimensional ocean circulation model based on the Intergovernmental Panel on Climate Change's four Representative Concentration Pathway (RCP) atmospheric CO2 scenarios (RCP 8.5, 6.0, 4.5 and 3.0 – from no mitigation of emissions to strong mitigation; Figure 8) (IPCC 2013). Using this as a basis, the researchers exposed Antarctic krill eggs to six different $CO_2$ levels (equivalent to 380, 1000, 1250, 1500, 1750, 2000 parts per million) until they hatched.

They found egg hatch rates significantly decreased at and above $CO_2$ levels of 1250 ppm, with almost no hatching at 1750 and 2000 ppm. They also found that embryonic development was significantly impaired if the eggs were exposed to 1750 ppm $CO_2$

**FIGURE 8:**
Trajectories of atmospheric $CO_2$ concentration under the Representative Concentration Pathway (RCP) scenarios of the Intergovernmental Panel on Climate Change (IPCC 2013).





The Antarctic krill, *Euphausia superba*.

during the first three days following spawning, even if the eggs were returned to lower $CO_2$ conditions after three days. The resulting risk maps showed that parts of the present important habitat for krill in the Southern Ocean will be at affected by year 2100 under under RCP 6.0, and with more severe consequences under RCP 8.5 (Figure 9).

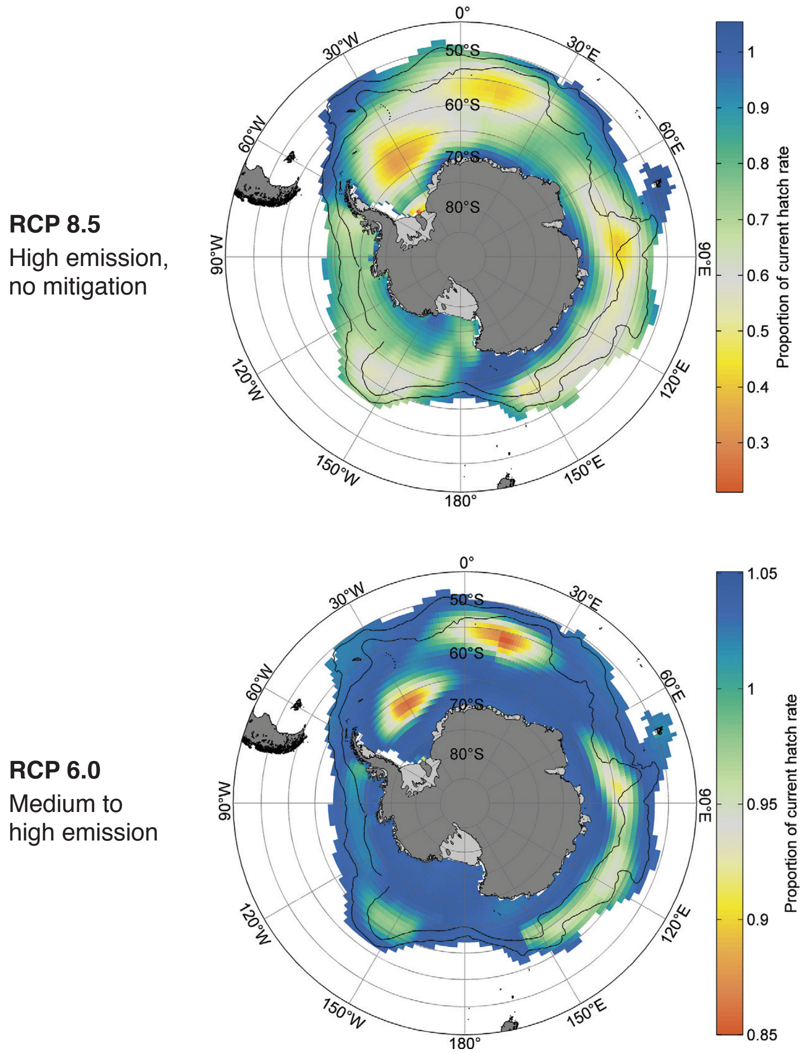
This finding is particularly critical, as krill eggs sink from the surface ocean and hatch at 700–1000 metres, where $CO_2$ levels are higher than present day atmospheric levels. The larvae then have to swim back to the surface to feed. A delay in their development would compromise their ability to do this, or even prevent them from reaching the surface before their energy reserves were exhausted.

The current atmospheric $CO_2$ concentration is about 405 ppm, but in some regions of the Southern Ocean the current maximum $CO_2$ concentration below 200 m depth reaches 550 ppm. $CO_2$ levels in deep water will continue to increase as atmospheric $CO_2$ increases, changing the chemistry of the water towards more acidic conditions.

Russ Hopcroft

*Limacina helicina antarctic* - a zooplankton with a chalk-like shell.

**FIGURE 9:**
Hatching success under an IPCC high carbon dioxide emission scenario for 2100 (upper panel) and a medium emission scenario for year 2100 (lower panel). Note the different colour scales on each panel. The southern-most black line shows the northern branch of the Southern Antarctic Circumpolar Current Front, and the northern-most line shows the middle branch of the Polar Front (adapted from Kawaguchi et al. 2013).



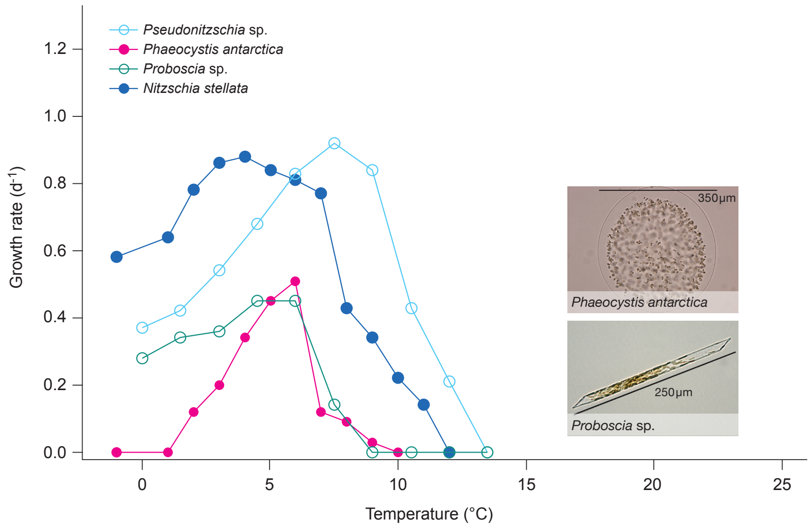
# PHYTOPLANKTON

To understand the significance of ocean warming on key phytoplankton species, researchers have conducted what are known as thermal performance curves (Boyd 2019). These experiments were designed to understand what range of temperatures the selected species can tolerate, and how this gradient might relate to the seasonal range in temperatures in polar waters (Figure 10). For most of the species examined they thrived within a temperature range that reflected the polar waters in which they reside, and which suggested that they were well adapted to this cold water environment. The experiments also suggested that overall phytoplankton activity is likely to increase significantly, with phytoplankton in the sub-Antarctic Southern Ocean potentially being able to grow at almost twice their current rate by 2100 (Boyd et al., 2016).

However, in a number of cases, phytoplankton species had a very sharp cut-off at temperatures just above the normal range, indicating a potential sudden tipping point under a future climate scenario.

Plankton come in many shapes and sizes.

**FIGURE 10:**
Thermal performance curves used to understand what range of temperatures the selected polar phytoplankton species (right) can tolerate, and how this range might relate to the seasonal gradient in temperatures in polar waters (modified from Boyd, 2019).



Other species, such as *Chaetoceros neglectus*, thrived in warmer waters, suggesting a potential future 'winner' under climate change (Figure 11). Additional work is needed to assess how common these polar species that seem to be quite comfortable in warmer conditions might be. The results also showed a conspicuous interplay with other environmental factors such as iron supply, with low iron altering the thermal performance of these diatoms and other polar bloom formers (Figure 12).

Thus, while some species are likely to benefit significantly, others are likely to suffer declines in productivity. Therefore it is too early to say how this will affect the broader structure of the ocean ecosystem. Whether these changes will tend to favour the larger diatoms preferred by krill, or the smaller, flagellated phytoplankton preferred by copepods is at this stage unknown. The likely impacts on the higher order species such as fish and mammals is also unknown. However, experiments such as these will eventually enable development of more sophisticated models for predicting system-wide changes to marine ecosystems resulting from climate change.

**FIGURE 11:**
As for Figure 10 but including the thermal performance curve for another polar species, *C. neglectus*, that can probably thrive in warmer waters, suggesting a potential future 'winner' under climate change.

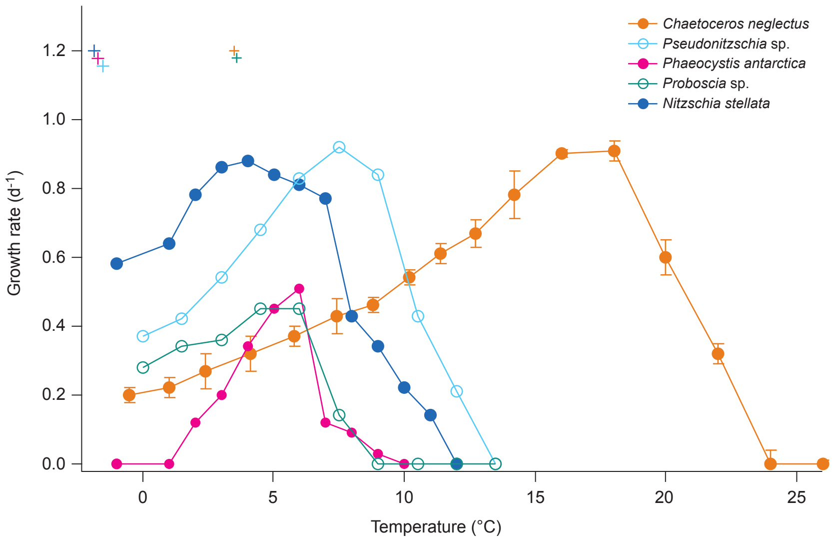
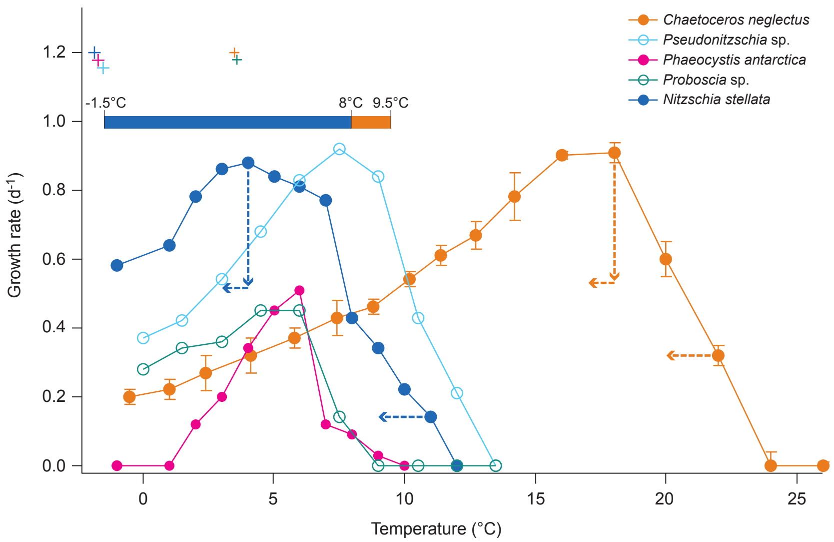



**FIGURE 12:**
As for Figure 11, but including the effects of iron limitation on growth rates: 1) a reduction in the optimal growth rates (vertical dashed arrows); 2) a decrease in the optimal growth temperature (adjoining horizontal dashed arrows); and 3) a decrease in the highest temperature at which the phytoplankton can grow (horizontal arrow in the far right of each curve). The blue horizontal bar represents the annual range of present-day temperatures across the Southern Ocean within an Earth System Model. The orange horizontal bar is the projected warming for the Southern Ocean by 2100.



# SUMMARY

### Key Activities

Using a combination of pilot studies, and existing research, ACE CRC scientists have identified key target organisms.

Successful pilot studies to 'stress test' key phytoplankton and krill species under future temperature and $CO_2$ scenarios.

Experiments on entire food webs – apex predators excepted – on board the Marine National Facility, *RV Investigator*, in subpolar waters.

### Key Outcomes

First evidence of what the dominant drivers might be for ecosystem change in the Southern Ocean.

Preliminary evidence of potential biological tipping points for key phytoplankton and krill species, including winners and losers.

### Future Challenges

Expand coverage to many different habitats, organisms across the food web with a combination of stressors.

Develop a more complete picture about how these potential shifts will play out at the food web level.

Provide data and research findings to ecosystem modellers, research community and end users such as IPCC (SROCC, AR6), SCAR and CCAMLR.

Figure 13 illustrates the many permutations of manipulation experiments that can be run across a wide range of polar life, habitats (open waters, sea ice, polar, subpolar) and oceanic properties. The research on this topic has focussed on key players in the Southern Ocean such as krill and bloom-forming phytoplankton such as diatoms. Other experiments have targeted calcifying phytoplankton and zooplankton such as coccolithophores and pteropods. The coverage of open water has been more comprehensive so far than for sea-ice biota. This trend is due to logistical difficulties in mimicking sea-ice conditions in the laboratory. Life from polar and subpolar regions has had a comparable level of scrutiny within this ACE CRC project.

Most of the lab experiments have focussed on single driver manipulations, mainly temperature and ocean acidification. In a few cases, such as microbes and diatoms, the influence of multiple drivers was explored using 2 and 5 drivers, respectively. In only one case was the pelagic foodweb (within 200 L mesocosms) targeted in the multiple driver experiments.

**FIGURE 13:**
Report card structure that denotes (ticks) which marine biota have been studied in climate change manipulations by ACE CRC researchers, and which environmental properties were altered in each study. Polar organisms are dark blue ticks, subpolar organisms are light blue. DOC is dissolved organic carbon. Empty cells reveal the current gaps in coverage across the report card for both organisms and environmental drivers.

| | Temp | Acidification $CO_2$ | Irradiance (UV or incident) | Oxygen $O_2$ | Nutrients, iron, salinity etc. Others |
|---|---|---|---|---|---|
| Krill | ✓ (Polar) | ✓ (Polar) | ✓ (Polar) | | |
| Copepods | | ✓ (Polar) | | | ✓ (Subpolar) |
| Pteropods | | ✓ (Polar) | | | |
| Microzooplankton | ✓ (Subpolar) | | | | ✓ (Subpolar) |
| Diatoms | ✓ (Polar) ✓ (Subpolar) | ✓ (Polar) | ✓ (Polar) | | ✓ (Polar) |
| Coccolithophores | ✓ (Subpolar) | ✓ (Subpolar) | ✓ (Subpolar) | | |
| Sea ice algae | ✓ (Polar) | ✓ (Polar) | | ✓ (Polar) | ✓ (Polar) |
| Marine bacteria | | | | | ✓ (Subpolar) |

Polar   Subpolar

Figure 14 below provides a synthesis of the nature of the responses observed across the range of manipulation studies.

A range of outcomes is evident from Figure 14, ranging from very positive to negative in response to either a scenario-based (such as IPCC projections for the year 2100 under a particular emissions trajectory) or a mechanistic approach (for example, testing the response across a range of temperatures to derive a performance curve, see Boyd et al., 2018 for more details). Stepping through the report card from krill to microbes this range of responses can be summarised as follows:

Rates of respiration in krill increased with ocean acidification from year 2100 $CO_2$ concentrations to 4000 ppm $CO_2$ (an extreme future scenario!) and then decreased to zero (Ericson et al., 2018). Interestingly, embryos were more susceptible to acidification effects than adults (Kawaguchi et al., 2013). Studies of the response of krill to warming revealed the thermal performance of krill was optimal at 0.5°C to 1°C and declined at lower and at warmer temperatures (Brown et al., 2010; Atkinson et al., 2006), suggesting a warming polar ocean (by 1.5°C in 2100) will have a negative effect on krill physiology and potentially alter the areal extent of suitable habitat for krill. In the case of manipulation studies on other zooplankton such as copepods and pteropods, acidification had detrimental effects on the former, and unclear outcomes on the latter group. Specifically, hatching success

**FIGURE 14:**
Report card denotes the responses of the marine biota (polar experiments are denoted by purple symbols, studies with subpolar species are green) during climate change manipulations by ACE CRC researchers. + represents positive responses such as an increase in growth rate, ++ a very positive response, nc denotes no change in performance under such year 2100 conditions, – is a negative response such as reduced hatching success, and – represents a detrimental response. In some cases, such as for coccolithophores +/- represents a mixed response across different species.

| | Temp | Acidification | Irradiance (UV or incident) | Oxygen | Nutrients, iron, salinity etc. |
|---|---|---|---|---|---|
| | | $CO_2$ | | $O_2$ | Others |
| Krill | (–) | (–) | (–) | | |
| Copepods | | (+) | | | (nc) (+) (foodweb) |
| Pteropods | | (–) | | | |
| Microzooplankton | (+) | | | | (nc) (+) (foodweb) |
| Diatoms | (++) (++) | (nc) | (nc) | | (+) iron (++) iron + temp |
| Coccolithophores | (+) | (+) (–) | (+) (–) | | |
| Sea ice algae | (+) | (+) | | (–) high $O_2$ (nc) low $O_2$ | (+) |
| Marine bacteria | | | | | (+) (iron, DOC) |

Polar  Subpolar

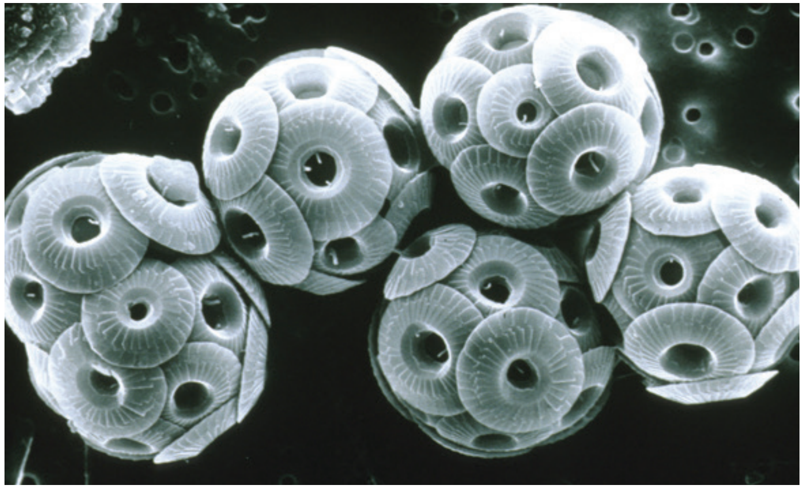
decreased and there was evidence of sub-lethal effects resulting in deformations. Over the four-year period, a sole study was conducted on a pelagic community that incuded copepods and microzooplankton (smaller grazers from 20 to 200 microns) and in which light, $CO_2$, temperature, nutrients and iron were jointly manipulated. The short-term (seven-day) study was too short to track any changes in copepod stocks or life history, but there was evidence of altered grazing rates by the microzooplankton (Boyd, unpublished data).

Moving down the foodweb, the report card also summarises the influences of a changing climate on phytoplankton – specifically diatoms, and coccolithophores in the water column and sea-ice algae who subsist mainly on the underside of the sea ice. In contrast to most of the zooplankton manipulation studies, the diatoms responded positively to increased temperatures, higher iron supply, and showed little change in response to ocean acidification. There were species-specific responses to temperature with a range of thermal performance curves evident across the diatoms (Figures 10-12). The coccolithophores, calcifying phytoplankton, exhibited a range of responses – positive and negative – depending on the species or strain to each of warming, acidification and altered underwater irradiance. In the pelagic foodweb experiment, discussed above, the diatoms responded positively as might be expected based on their positive response to each of iron supply and warming. There were very few coccolithophores present in this natural community experiment in subpolar waters and so it was not possible to assess their response to climate change.

Australian Antarctic Division

The Antarctic krill, *Euphausia superba*.

In the case of sea-ice algae they responded positively to temperature, and in some cases to higher irradiances. The microbes – hetrotrophic bacteria of < 2 microns – responded positively to increased supply of dissolved organic carbon (DOC) that might result from projected increases in phytoplankton primary production by year 2100 (Moore et al., 2018). They also benefited from increased iron supply.



A coccolithophore is a unicellular phytoplankton. Coccolithophores are of particular interest to those studying global climate change because as ocean pH decreases, their coccoliths (a chalk-like microscopic plate) may become even more important as a carbon sink.

Although a wide range of marine biota, drivers and habitats were involved in this four year study, it is too early to be able to draw a comprehensive suite of conclusions. In some cases the outcome of experiments – such as using diatoms – corroborated the projections from modelling studies on future positive trends in primary production for the Southern Ocean (Moore et al., 2018). But the similar outcomes were attained for different reasons. This research synthesis will provide a platform to further develop this theme during the recently funded Australian Antarctic Program Partnership (AAPP) as part of the Antarctic Science Collaboration Initiative program. The successful funding of the decade-long AAPP will further develop research sub-themes that target assessment of the responses of phytoplankton, krill and other zooplankton – which are likely to compete with krill under changing Southern Ocean conditions. Hence, this emerging research into the potential tipping points, that may exist as the Southern Ocean and Antarctica are altered in response to anthropogenic change, can be comprehensively tested and used to inform modelling initiatives. Such a suite of model projections will ultimately inform political decisions by groups such as CCAMLR.

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Seals playing in sea ice.


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