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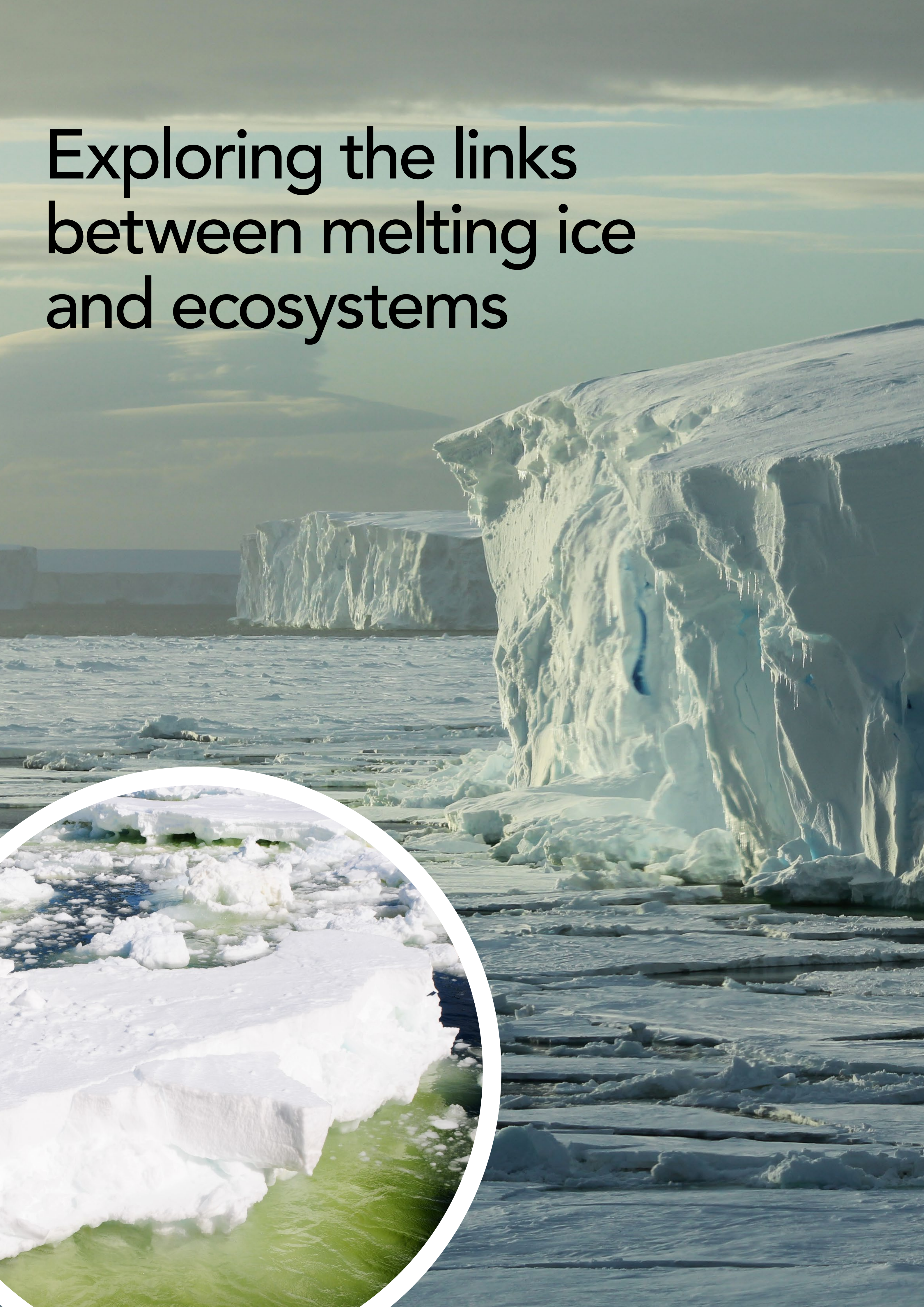

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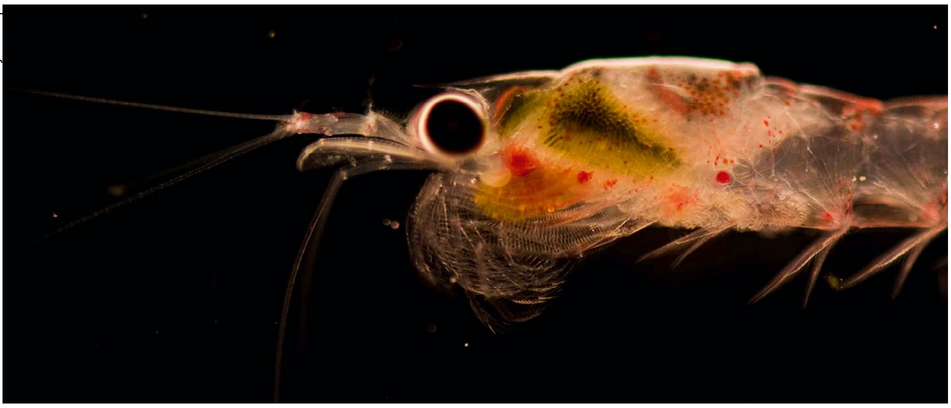
Increased melting of ice sheets and losses of seasonal sea ice are both commonly reported consequences of climate change that can impact polar marine ecosystems. Ice sheets are thick masses of land-based glacial ice that can extend out over the ocean in the form of ice shelves. Sea ice is much thinner and comes from freezing the surface ocean. Although we usually focus on melting ice sheets affecting sea level rise, it turns out that they can also impact the coastal ecosystem nearby. Meltwater from ice sheets may deliver nutrients to fertilise coastal phytoplankton blooms. In polar regions, where light can also be limiting to blooms, seasonal sea ice is an important part of ecosystem development. Normally, spring melting of seasonal sea ice stabilises the ocean surface layer, which helps phytoplankton to stay in the sunlit zone where they can photosynthesise and bloom as long as there are adequate nutrients. But if nutrient supply does not coincide with periods of light exposure and stability from sea ice melt, then a vital component for phytoplankton growth is missing. This scenario hints at the complexity and vulnerability of ecosystem response to climate change, which raises questions that Professor Patricia Yager and her colleagues are beginning to answer.

At the University of Georgia, Professor Yager collaborates on the INSPIRE (Investigating the Role of Mesoscale Processes and Ice Dynamics in Carbon and Iron Fluxes in a Changing Amundsen Sea) project with scientists from Old Dominion University, Rutgers University and the University of Colorado. The INSPIRE project builds on the field observations collected during a research expedition in 2010–11 by the ASPIRE project (the Amundsen Sea Polynya International Research Expedition). Both projects were supported by the US National Science Foundation and involve a multidisciplinary team of physical scientists, biologists and biogeochemists. INSPIRE will use their insights and experience to refine existing computer models with the aim of identifying the factors that contribute to the productivity of the Amundsen Sea polynya.



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**Melting ice sheets affect more than just sea level – ecosystems also respond to changing ocean processes**

### WHAT ARE COASTAL POLYNYAS?

A coastal polynya is a recurring area of open ocean surrounded by sea ice and often located just beyond the edge of an ice shelf. Examples exist along the coasts of Greenland and Antarctica and they are formed from the effects of persistent local offshore winds that create an embayment that is bounded by sea ice. The Amundsen Sea polynya is located in the South Pacific Ocean sector of West Antarctica, in one of the least studied Antarctic regions. It is of scientific interest for several reasons: the glaciers here are experiencing the fastest melting rates of any in Antarctica and the seasonal sea ice cover offshore of the coast is rapidly decreasing at rates comparable to Arctic sea ice loss. On a more positive note, the Amundsen Sea is one of the greenest and most ecologically productive areas in the world, and the phytoplankton growing there facilitate a significant deep storage for carbon that is sequestered from the atmosphere.

### WHY PHYTOPLANKTON THRIVE

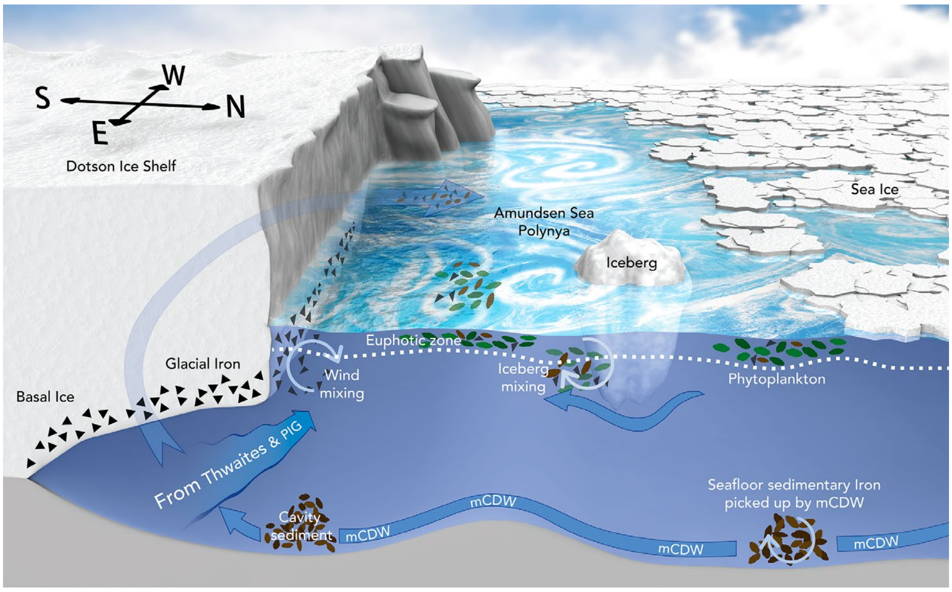
Phytoplankton are important because they form the base of the marine food web and higher organisms rely heavily on them. They thrive in the Amundsen Sea because they receive sufficient light and nutrients to bloom. Dissolved iron is one essential nutrient that phytoplankton require, and the melting ice sheet contributes to the fertilisation process. According to the team's model, only some of the iron is derived directly from the ice sheet meltwater, however. Instead, as the meltwater mixes with warm, salty, deep ocean water, its low salinity provides buoyancy that lifts iron-rich deep water closer to the surface, making it accessible to phytoplankton. The model suggests that some of the iron comes from deep waters off the continental shelf but even more is released from local seafloor sediments. The INSPIRE team has modelled this so-called "meltwater pump" concluding that ice sheet melting has an important role in nutrient supply and ecosystem survival. They are currently testing the idea that this pump controls polynya productivity and thus the amount of carbon that is sequestered in the region.

### MODELLING A COMPLEX SYSTEM

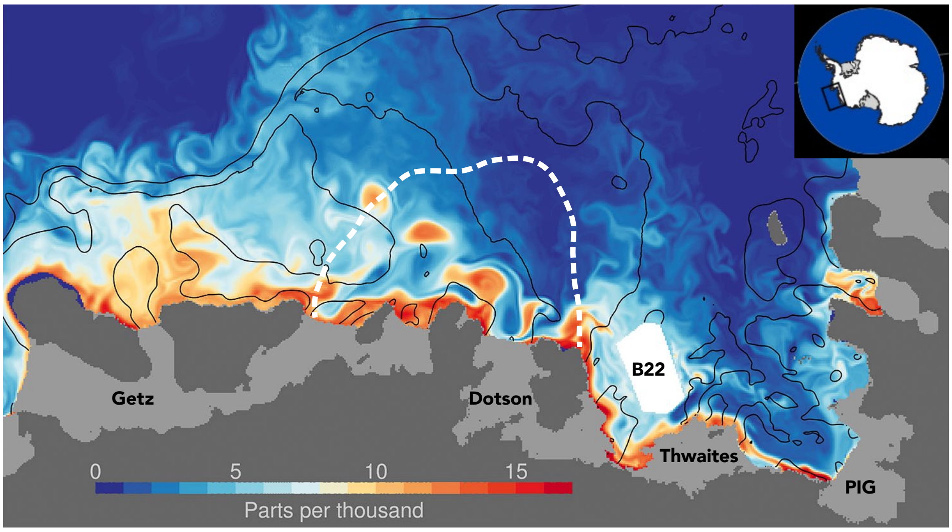
Variability of ecosystem productivity in the Amundsen Sea Polynya from one year to the next suggests a strong sensitivity to climatic conditions. Remote sensing data have shown that annual productivity in the

Amundsen Sea may be explained partially by rates of glacial melt, but that sea ice dynamics and winds are also important. This finding suggests that ecosystems controlled by multiple factors may be more sensitive to climate change but are also less predictable. Because climate variability and change cause a range of impacts, what might suit some aquatic species may have undesirable consequences for others.

The collaborative INSPIRE project aims to understand the consequences of human induced climate change upon the ocean ecosystem using a computer model developed to simulate ocean circulation in the Amundsen Sea and its interactions with ice. They will add biogeochemistry to the model and validate it using field observations from previous field projects. The model has been used recently to investigate four potential inputs of iron: circumpolar deep water, glacial meltwater, deep sediments and sea ice. Professor Yager and her colleagues have demonstrated that the melting ice shelves are crucial for supplying iron both directly and indirectly (via the meltwater pump) and have corroborated the meltwater pump theory with observations. Now that the model has been validated using present-day observations, the next step is to model future climatic conditions to look at how physical changes may affect the ecosystem in future.




Cutaway diagram of the Amundsen Sea Polynya showing processes thought to contribute dissolved and particulate iron to the polynya water column. *mCDW – Modified Circumpolar Deep Water: warm and salty seawater from offshore cascades into ice cavity to melt ice shelf.




Model output showing the iron-rich waters being delivered from the ice shelves to the waters offshore during summer. The white dashed line is the approximate area of the open polynya. Legend indicates the concentration of meltwater in parts per thousand. Notice the circular eddies of iron-rich water being shed off the coastal current into the central polynya. The light grey areas are ice shelves, the dark grey areas are part of the Antarctic continent. A large grounded iceberg (B22) is also shown. Black lines are 500 m and 1000 m depth contours. Inset shows the location of the Amundsen Sea in West Antarctica.

**LOOKING TO THE FUTURE**

Accelerated rates of ice sheet melting will lead to increased freshwater inputs to the Amundsen Sea polynya that have the potential to change the physical, biological and biogeochemical characteristics of this system. If the processes driving the meltwater pump intensify in the future, the polynya may become more productive and consequently a greater sink for carbon in the short term. However, long-term effects are more complex and difficult to predict. A declining trend in both the geographical extent of summer sea ice and the length of the sea ice season is forecast to continue. The worst-case scenario would be a total loss of sea ice, which means that the polynya could be erased by permanently open water with lower productivity. This outcome would then have negative consequences for the penguins, seals, and whales that currently thrive there. A well-constructed model will help the team assess the net impact of these future changes on the ecosystem.

Professor Yager's collaborative research has revealed compelling evidence to support the idea that ecosystems have many linkages and co-dependencies with the climate system and that ecosystems are being altered or perturbed in response to changing climatic conditions. Furthermore, the research suggests that these changes are not necessarily advantageous. Understanding ecosystem response to the impacts of climate change is therefore of great importance when considering strategies for mitigation and adaptation.

**Ecosystems are not necessarily changing for the better. To mitigate or adapt to change, we need a better understanding of all the processes involved**

# Q&A

***What gets you excited about ecosystem research?***
Two things move me the most. Firstly, I love seeing polar marine wildlife from the deck of the ship (or if I'm really lucky, from out on the sea ice). I'm especially fond of penguins, but also minke whales, crabeater and Weddell seals, and various other seabirds. Second, I am most excited when I get to play with "all the puzzle pieces". Interdisciplinary science has always been my love. Seeing how the motions of the water and ice, the chemistry of the water, and the shape of the seafloor, all interact with the ecosystem: that has always fascinated me. Understanding climate change is important to both these passions.

***What has been the most interesting finding from your research so far?***
The biggest surprise was discovering that the meltwater itself is not the only source of iron to the polynya. The indirect effects of the "meltwater pump," the fresh meltwater lifting up iron-rich deep water was really exciting to discover. The sediment contributions to deep water iron were also something we hadn't really considered since the Amundsen shelf is so deep and usually isolated from the surface. These two iron sources in combination with the meltwater pump provide a real boost to the phytoplankton.

***What are the other physical processes that might be driving sea circulation and nutrient supply?***
The other big contributor is the winds, and the winds are changing in response to climate change. That's one reason we don't just use "global warming" anymore. The warming has triggered all of these other changes to the climate system. Changing westerly winds are likely to affect how much warm water comes onto the shelf to melt the ice shelves. Katabatic winds flowing off the continent will also determine the extent of convection and sea ice production in the winter, which likely sets the stage for the spring bloom. Understanding the changing winds will be important to future projections. (Katabatic means "descending", and katabatic winds descend off the high topography of the Antarctic continent under the force of gravity, reaching great speeds as they flow off the coast.)

***What are the biggest unknowns with this project?***
The biggest unknowns are really how much and how fast the ice sheets will melt in the future. It's hard to project future impacts on the polynya if we don't know what the ice sheets will do. A new initiative is underway to make progress on this front.

We also don't yet know how to distinguish meltwater that comes from the ice shelf face versus that which flows like a river from underneath the glacier. These two types of meltwater could contribute iron differently, now and in the future. We are currently working with glaciologists to try to make headway here.

Finally, we don't really understand how the iron cycles through the ecosystem. For example, we don't know if the phytoplankton take up the dissolved iron directly, or if bacteria living in the "phycosphere" are the ones in charge of collecting it and then handing it out. How the iron is recycled by microorganisms in the surface ocean is also virtually unknown. We are currently adding more biology to our model to test the sensitivity of the ecosystem to iron recycling.

Ultimately, we would hope to return to the region to test whether our model projections are accurate.

***How important is the Amundsen Sea as a carbon sink?***
The Amundsen Sea takes up $CO_2$ from the atmosphere at a rate 10x faster (per unit area) than the average rate for the Southern Ocean. That's very important. This high uptake rate makes it a real "hot spot" for carbon sequestration. Although we know the region is an efficient carbon sink from the atmosphere during the summer, further study is needed to understand the length of time (e.g., decades, centuries, millennia?) that the carbon will reside in the subsurface ocean, away from the atmosphere. Computer models should be able to tell us the residence time and the fate of these high $CO_2$ deep waters, predictions that can then be tested with targeted observations from ships or autonomous vehicles.

# Detail

**RESEARCH OBJECTIVES**
Prof Yager and her collaborators are currently working on the INSPIRE project investigating how present and future climate change impacts coastal Antarctica. Their aim is to use a computer model of the ocean to generate new insights and hypotheses that will ultimately guide sampling strategies of future field efforts.

**FUNDING**
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**COLLABORATORS**




- Pierre St-Laurent (Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, Virginia USA)
- Robert M. Sherrell (Department of Marine and Coastal Sciences and Earth and Planetary Sciences, Rutgers University, New Brunswick, New Jersey, USA)
- Sharon Stammerjohn (Institute of Arctic and Alpine Research, University of Colorado Boulder, Boulder, Colorado, USA)
- Mike Dinniman (Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, Virginia, USA)

**BIO**
Patricia Yager received her PhD in 1996 at the University of Washington School of Oceanography and is now a Professor in the Department of Marine Sciences at the University of Georgia. Her research concentrates on the connections between climate and marine ecosystems, and includes both fieldwork and modelling.

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